METAL AIRCRAFT CONSTRUCTION

BY

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A REVIEW FOR AERONAUTICAL ENGINEERS
OF THE MODERN INTERNATIONAL PRACTICE
IN METAL CONSTRUCTION OF AIRCRAFT

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PREFACE

TO FOURTH EDITION

THE fourth edition of *Metal Aircraft Construction* is considerably larger than the earlier ones, and many changes have been made. Out-of-date material has been eliminated except where it is of basic technical interest, and much new matter, particularly relating to the American aircraft, has been added. I have to thank Mr. Lester D. Gardner for his help in persuading the American Aircraft Industry to assist in compiling the book. They came forward generously after he had approached them on my behalf.

The particulars of aircraft of the belligerent countries are of necessity scrappy. This is especially true of German aircraft, as the revision had been completed before so many fine specimens fell into British hands. Descriptions of these are, however, appearing weekly in the technical press. The descriptions of French, Polish, and Czechoslovakian structures stand as they did on the eves of the German occupations of those countries.

In earlier editions I was able to quote a list of all the people who had actually helped in their preparation. Whilst thanking everyone who has assisted in this work, a complete list of them all would be too long, and it has been decided to leave it out. Two, however, must be named, Captain J. Laurence Pritchard, and the late Richard Langley, A.M.I.Struct.E., my brother, whose help and encouragement made the original work possible.

THE MATERIALS OF AIRCRAFT CONSTRUCTION

BY

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THIS practical book embraces the complete range of materials used in the construction of aircraft. It discusses each material individually from the point of view of its properties, production, treatment, and special applications. The volume is primarily for the student of aeronautical engineering working in this particular field, but all interested in the various problems concerned with aircraft design will find it excellent for study and reference.

CONTENTS (ABBREV.): Mechanical Testing—Steel and Iron—Steel Tubing—Streamline Wires—Steel Wire, Ropes, and Cables—Non-ferrous Light Alloys—Copper-Tin Alloys—Corrosion—Timber—Varnish and Protective Coverings—Glue and Gluing—Rubber—Fabrics and Dopes—Selection of Materials—Appendices.

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METAL AIRCRAFT CONSTRUCTION

CHAPTER I

THE DEVELOPMENT OF METAL AIRCRAFT

THE construction of aircraft in metal has passed the stage when it requires advocacy. The arguments and discussions which stirred technical meetings fifteen or twenty years ago have lost their point. Metal construction has become an accomplished fact, and there is barely a machine designed to-day for any other material, except in the light aeroplane class.

It will perhaps be interesting, however, to go back and review the change-over from wood to metal and to remember the arguments.

There were metal aeroplanes in the early days,[1] before the War, 1914–18, changed construction from an experiment to an industry. The R.E.P., the Martinsyde Pusher,[2] the Clement Bayard and the Seddon efforts will be remembered. But at that time the aerodynamical problem was more urgent than the constructional one. Wood and fabric were easily available and cheap. The light alloys had barely been developed, and high tensile steel was not only expensive but in the forms then made not particularly suitable. Extensive production of a type was unknown and development so rapid that the laying down of costly plant was not justified. With the obvious materials, then—wood and fabric—these pioneers built machines whose principal requirement was that they should fly.

When war broke out, they had produced something which was quickly realized to be of immense military value. The demand was enormous, and scattered sheds at Brooklands and Hendon were the nuclei from which great firms sprang. Suitable timber was at a premium, not only because of the demand, but because it had to be imported, using ship space which was urgently needed for food and troops. Forests were cut down and still the demand grew. Spruce was the principal timber used, but substitutes had to be found. Other woods were suggested and tried—hickory, larch, Port Orford cedar, cypress, and poplar—with little success. The inevitable happened. Just as metal had replaced wood in the building of ships and machinery, so it was realized that it must replace it in the building of aeroplanes. Experiments were begun and towards the end of the war metal wings and fuselages had been produced.

With the cessation of hostilities, the demand for military machines died out and the factories were at a standstill. It was several years before the vast number of completed but unused wartime aircraft were absorbed or broken up at scrap prices. Civilian companies formed to operate air transport, joy riding, air survey, etc., found it infinitely cheaper to use these fighting machines, converted to suit their requirements. Technical advances were hindered by lack of money and the absence of demand for new types, and it was some six years before a revival set in. All honour must be paid to those who laboured on during that period, with so little encouragement, to accomplish what they knew would be inevitable. The Short Brothers, Major F. M. Green and the Armstrong-Whitworth Co., Ltd., Major Wylie, Mr. J. D. North and Messrs. Boulton & Paul, Ltd., the Steel Wing Co., Ltd., are some who deserve mention. But the Royal Air Force continued to use the same types which had served them so well, and civil aviation was as yet a penniless child.

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[1] See Letter from A. R. Weyl, *Journ. R.Ae.S.*, Feb., 1934.

[2] Built for Commander Guy Blatherwick, R.N.

An improvement could be seen in 1924, and the following year the tide began to turn. The demand for equipment of newer design was closely followed by an Air Ministry order that all future designs for their own use must be worked out in metal. The shortage of timber which had tended to hamper production at the end of the last war must not be a hindrance in the next. Metal ores, even though imported, were a much less bulky cargo than wood. And the country was well fitted in its great metal-producing industries to tackle the special research which would be necessary.

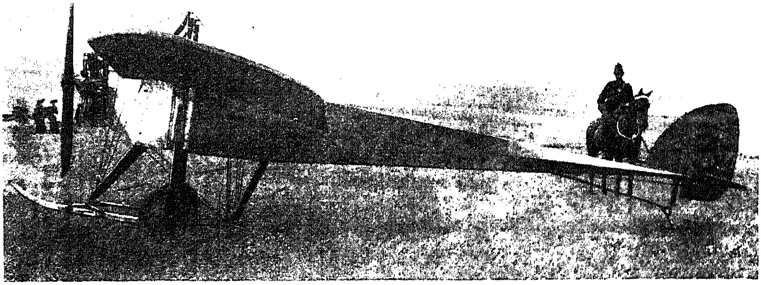

FIG. 1. THE VICKERS R.E.P. MONOPLANE WITH STEEL TUBE FUSELAGE
(By courtesy of "Flight")

A step in the change-over at this point was that existing wooden aircraft were ordered for the Royal Air Force to be re-designed in metal. The aerodynamical problem was shelved temporarily and designers concentrated on the constructional one. The metallurgist, the scientist and the mathematician undertook research, and the engineer interpreted and applied their results. The production of alloys and light metals of less weight and greater strength, the treatment of them to make their manipulation easier, were studied and new troubles of instability, fatigue, and corrosion examined in greater detail than ever before. It soon became possible to compare machines of exactly similar aerodynamical characteristics, but of different materials. The results were not only encouraging; they were convincing. The all-metal aeroplane had arrived, but the way of its coming influenced subsequent design in England, in that it was barely possible to distinguish the metal from the wooden machine without an examination of the internal structure. Similar developments took place in France and America. In the latter country, however, the coming of metal construction coincided with the great economic boom of 1929–30, and a large new civil aviation industry came into being like a mushroom growth. Anything would sell, and the methods which had been painfully built elsewhere were adopted wholeheartedly to meet the demand.

Later America took up the low wing monoplane of stressed skin construction, wing flaps, and the retractable undercarriage. These had all originated elsewhere but by developing them and using them to their best advantage she produced a number of types which set a new fashion in civil and military aircraft.

In Germany, however, we find a different approach to the subject. Metal was not just used as a material to replace wood without further influence or thought. As long ago as 1910 Junkers had been granted a patent for what was essentially the "flying wing." He saw that the reduction of parasitic resistance went farther than the fairing-in of excrescences, and that the only part of an aeroplane which fully justified its existence was the wing. If this could be made to enclose all else—the power plant, crew, tanks and useful load—then an enormous step forward would have been made and parasitic resistance at a minimum. This implied that the wing should be large and, if necessary, thick. Experiment and research showed that thickness in the wing section was not necessarily a bad feature. The next point was construction, and an examination of available materials showed that wood was unsuitable and that his conception could only be carried out efficiently in metal. To quote him, "Wood is obtainable only in fixed sizes and shapes of trunk and branch furnished by Nature, whereas metal may be obtained in a nearly unlimited variety of qualities and dimensions."[1] Furthermore, it can be shaped into any form, is more reliable, and its strength can be forecast and is unaffected by climate and atmospheric conditions. It appeared to him the only possible material with which to construct his giant.

The first firm in Germany to build all-metal aircraft of "Duralumin" was, however, the Dornier Company. They began in 1914 with a large flying boat of over 120 ft. span (see Fig. 2). This was the forerunner of a number of large flying boats and seaplanes used by the Germans during the war.

The economic depression following the war was further influenced by the restrictions on aircraft development in Germany, imposed by the Treaty of Versailles. Eventually, however, Junkers was able to produce his G.38, which was a step on the way to the ultimate realization of his flying wing. This different approach to the subject in Germany, whereby the aerodynamical design is only made possible by the use of metal, is further shown by Dr. Dornier's development of his early flying boats up to the *Do X*. This could certainly have never been built in any other material but metal.

A further point which has not yet been mentioned is the reduction of structure weight which has been obtained in metal machines. That this would be so was prophesied, but doubted in many quarters, until proved in actual fact. The subject of "specific tenacity," or the relation of the strength to the specific gravity of a material, will be further considered in the next chapter. It is sufficient to state here that surprising reductions of weight have been made, particularly in the larger machines. Metal does not show up to the same advantage in small aircraft of the 100 h.p. two-seater class, since strength for strength the metal member becomes too fragile to be handled and the greater bulk gives wood a substantial claim. It is difficult to say where the dividing line between greater efficiency in wood or metal falls. Roughly, it may be said to occur at a machine with an all-up weight of 3,000 lb., but the service for which the machine is intended may have a considerable influence, as may also the labour and plant available. Wood may be said just to hold its own in the light aeroplane class and in medium-sized commercial and experimental machines.

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[1] "Metal Aircraft Construction," Professor Hugo Junkers, *Journal Royal Aeronautical Society*, September, 1923.

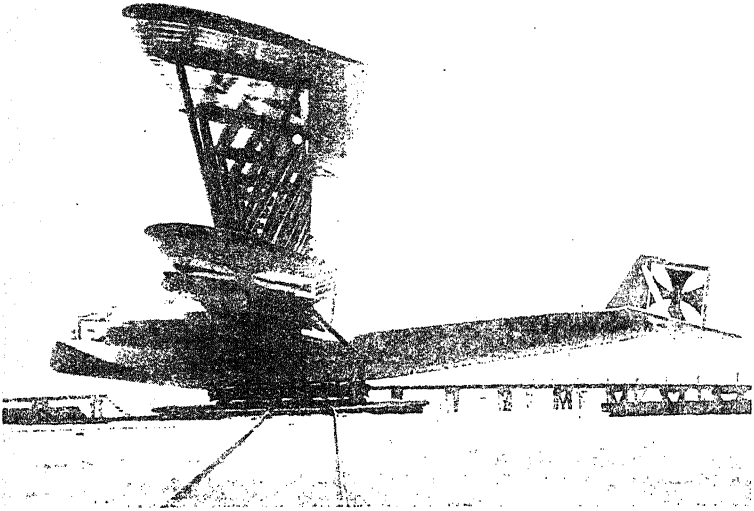

FIG. 2. DORNIER THREE-ENGINED FLYING-BOAT, TYPE R.S.1, 1914–1915
(By courtesy of Dornier Metallbauten G.m.b.H.)

We may summarize the advantages of metal as follows—

1. It makes possible the design of large aircraft which were previously constructionally impracticable.
2. Metal construction allows lighter structures for medium and large-sized machines.
3. It has greater reliability, being of a more homogeneous nature.
4. It is less affected by climate and weather.
5. It allows the making of more mechanically efficient and durable joints.
6. There is a considerable reduction in fire risks.
7. Metal can be worked into a much greater variety of sizes and

8. The life of an all-metal structure, if adequately protected, is considerably longer than a structure built of organic materials, and consequently the relative cost of construction is lower. This is particularly true of the use of stainless steel, the life of which is, for all practical purposes, infinite.

The argument that metal construction is more expensive applies only when special plant must be laid down for experimental and single machines. In large production there is no question that metal work may be made cheaper by the use of modern plant and methods. Interchangeability and standardization are possible to a degree which could never be realized in wood work.

CHAPTER II

MATERIALS

STEEL is a term which now covers a very wide range of materials, varying greatly in constitution and in properties. In all its forms, however, it is essentially an iron base with definite proportions of other added elements.

Chemically pure iron is almost unknown and has only been prepared in the laboratory, but commercially pure iron is produced electrolytically. Iron, as manufactured in the blast furnace, is a crude substance containing carbon, sulphur, phosphorus, silicon and manganese. This impure iron, known as pig iron, is the raw material from which carbon steel is made by removing the undesirable impurities as far as possible and adjusting the amounts of others. Alloy steels are obtained by the addition of such elements as manganese, chromium, nickel, vanadium, cobalt, molybdenum or tungsten to iron, with or without carbon, with the object of giving it such qualities as hardness or tenacity or non-corrodibility.

Pig iron as it comes from the blast furnace may contain anything from 2 to 4½ per cent of carbon, but in steel this is usually reduced to considerably less than 1½ per cent. Leaving for the moment the question of alloy steels and considering only the carbon steel group, we find a great difference in tenacity and ductility as the carbon content is varied. A mild steel with 0·15 per cent of carbon has an ultimate tensile strength of about 28 tons per square inch, but when the percentage is increased to 0·5 the strength has risen to something of the order of 50 tons, with an attendant increase in hardness and decrease in ductility. It is possible by adding carbon up to 1 or 1·25 per cent to reach a strength of over 120 tons per square inch, but the elongation is only 0–1 per cent. To obtain steels having high tensile strength, but at the same time great toughness and shock-resisting qualities, it is necessary to resort to the alloy steels. Both the plain carbon and the alloy steels are capable of considerable modification in their physical properties by the process of heat treatment. Whilst pure iron is little affected by this treatment, its effect becomes increasingly important as other materials are added. It cannot be too strongly emphasized that the strength of any steel is dependent on the thermal and mechanical treatment to which it has been subjected.

Manufacture of Iron. Though good quality iron ore does exist in small quantities in the British Isles, the largest deposits of ore, in Cleveland, Lincolnshire, and Northamptonshire, are low in iron and contain the impurities sulphur and phosphorus. The sulphur is present as iron pyrites and the phosphorus as phosphates. The sulphur is undesirable as it persists throughout the manufacture and is difficult to eliminate from the finished steel, where it produces a condition known as "hot shortness." The phosphorus is more easily removed and in certain processes of steel making it is definitely helpful. The iron in these ores is present principally as ferrous carbonate.

A large part of our steel is manufactured from iron derived from haematite ore (Fe_2O_3), mainly imported from North Spain. These ores are low in sulphur and phosphorus, and contain a high percentage of iron. Other countries which supply us with iron ores are Sweden, Norway, Greece and Algeria.

In 1927 the figures were as follows[1]—

Iron ore produced: £3,240,000 or 11,206,871 tons.
Iron ore imported: £5,441,000 or 5,163,793 tons.

Speaking generally, the foreign ore is richer in iron than the home product. This fact, together with the greater purity, accounts for the higher value of the smaller weight of the foreign ore quoted in the above figures.

It will thus be seen that, though Great Britain is one of the big steel-producing countries of the world, its supplies of material are to a great extent foreign.

The first stage in the manufacture of steel is the reduction of pig iron from the ore. The ore is calcined in coal or gas-fired kilns to drive out moisture and carbon dioxide, which would impair the efficiency and speed of working of the furnace. The blast furnace in which the reduction takes place is a large steel cylindrical structure, lined with fire-brick, of 60 ft. to 100 ft. in height and 18 ft. to 25 ft. in diameter. It is closed at the top with a movable cone and provided at the bottom with air nozzles and plugged holes through which the molten iron and slag can be run out at intervals. Alternate layers of calcined ore, coke, and limestone are charged at the top of the furnace, and a hot air blast at a temperature of about 550° C. and a pressure of about 6½ lb. per square inch is blown in through the nozzles, or tuyeres, near the bottom. The oxygen in this air coming in contact with the incandescent coke at a very high temperature combines with it to form carbon monoxide. This gas and the carbon in the coke reduce the iron oxide to metallic iron in the reaction zone of the furnace. The iron, combining with carbon, phosphorus, silicon, sulphur and manganese, forms a fluid product which collects in the well of the furnace.

The limestone is added to combine with the infusible gangue present in the ore, and the ash of the coke, to produce a fluid slag. This is tapped off through a slag notch placed above the level of the molten iron in the furnace. The pig iron is tapped periodically either into travelling ladles which convey it straight to the steel plant, or is cast in big sand beds at the furnace foot. The quality of the pig iron varies with the nature of the charge and blast conditions, and after each cast a quick chemical analysis of the result is made for use at the steel plant.

The process is a continuous one, and the output of a normal English furnace is 900 to 1,000 tons of pig iron per week.

Manufacture of Steel. The four processes at present in use for the manufacture of steel are the Crucible process, the Bessemer process, the Open Hearth process, and the Electric furnace process.

The Crucible process has been in use in this country since 1740, and still finds a limited application in the production of special high-grade tool steels. Essentially the process consists of melting together small quantities of pure materials, and no refining or elimination of impurities is attempted. Pig iron prepared in Sweden from very high-grade ore, in blast furnaces using charcoal as a fuel, forms the basis of the chief ingredient of the charge. From this pig iron a metal containing only traces of carbon, silicon, and manganese is obtained by oxidation with air blast in a Lancashire hearth furnace. This purified iron is removed from the furnace in a pasty condition (similar to the puddling process for making wrought iron), and the entangled slag is squeezed out by forging the bloom under a hammer. The iron is then rolled into bars about 2½ in. wide and ½ in. thick, which are cut up into small pieces for charging into the crucible. The remainder of the charge consists of the necessary amount of Swedish pig iron to adjust the carbon content to the desired amount, ferro-manganese, and the desired special elements either as pure metals or as alloys of iron. The crucibles are of a special clay composition and hold a charge of 60 lb., the melting being performed in a natural draught coke-fired furnace or a gas-fired one.

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[1] Whitaker, 1930.

The Bessemer process can be utilized for the conversion of two distinct grades of pig iron into steel. In the original process the furnace was lined with silica or quartzite, which is of an acid nature. This method, invented in 1855, was known as the Acid Bessemer process. In 1879 the principle and use of the process were considerably extended by the Basic Bessemer process, in which the furnace was lined with a basic material, calcined magnesian limestone or dolomite. The removal of phosphorus is effected by oxidation, and combination of the acidic oxide formed with a basic material to form a phosphate slag. The use of a slag of a basic nature is only possible when there can be no reaction between the slag and the lining. De-phosphorization is therefore restricted to the Basic process. In the Acid process, haematite iron containing about 0·06 per cent of phosphorus is used, and in the Basic process the iron usually has about 1·6 per cent of the element, together with a low silicon content. In each method of working, the charge of molten pig iron is poured into the Converter, which is an egg-shaped vessel, mounted on trunnions so that it can be rotated. Air at a pressure of 25 lb. per square inch is blown through the metal. The oxygen of the blast combines with the manganese, silicon and carbon, a reaction which generates considerable heat. At the end of about 20 to 25 min. an almost pure molten iron remains in the vessel. In the Acid process, the reaction is stopped at this stage, the metal is recarburized, and at the same time de-oxidized by the addition of ferro-manganese. It is poured into ladles, and cast into ingots for rolling. In the Basic process, the slag is poured off, lime is added and the "afterblow" commenced which eliminates the phosphorus, more than sufficient heat being generated to melt the new slag. The charge is then recarburized and cast.

The Open Hearth process is likewise operated on the Acid and Basic principles according to the type of iron to be dealt with, and either plain carbon or certain of the alloy steels are made in charges from 5 up to 75 tons in stationary furnaces and up to 150 tons in tilting furnaces. The hearth of the furnace is a large shallow bath on to which the pig iron, either solid or molten, is charged together with steel scrap and haematite ore. Heating is by producer gas and air, regenerative systems of heat economy being always used. The removal of carbon, silicon and manganese (and phosphorus in the basic lined furnaces) is by oxidation. But in both cases the reactions occur through the slag, which is therefore under perfect control. It is usual to reduce the carbon only to the required percentage, determined by a rapid chemical analysis. Any slight adjustment is made by adding ferro-manganese to the molten stream as it passes from the furnace to the ladle. In making nickel or chromium steel, or steel containing both these elements, in the Open

Hearth furnace, the additions are made shortly before tapping to ensure even distribution.

The Electric furnace is now very widely used for the manufacture of alloy steels. For large-scale production the arc type is the most generally used, and its application has developed rather as a remelting and refining furnace than as a converting unit. Exact scientific control of atmosphere and slag are attained, and fine limits of composition (impossible in other furnaces) upon which the value of certain special steels depend, are regularly obtained. A case in point is the production of low carbon chromium steels, and this is now achieved by the direct reduction of chrome ore in the furnace without the expensive intermediate stage of low carbon ferro-chrome alloys. High frequency induction furnaces are being developed for special steels.

The Physical Properties of Steel. Steel is the most generally used of all metals for engineering purposes, and though in aircraft construction it is challenged by others of lighter weight, it still holds its own for many purposes. The principal reasons for its popularity are the ease with which it can be manufactured in large quantities at a low price, and the variety of forms and uses to which it can be converted. It can be made strong and tough or soft and ductile, heat-resisting and corrosion-resisting. It can be worked into all shapes and sizes, forged, welded, cast or stamped. The claim that there is a steel for every purpose in engineering appears to be well justified.

The chemical analysis of a steel furnishes but one clue to its properties. Much depends on the form and the distribution of its constituents which may exist in the free state or in combination as compounds or solid solutions in varying degrees of dispersion throughout the mass. The condition of the constituents is very largely influenced by two factors—the heat treatment of the steel and the mechanical treatment.

Consider first the plain carbon steels, containing only the normal small amounts of manganese, sulphur and phosphorus, and the remainder iron and carbon. This carbon is present as a carbide of iron (Fe_3C) known as Cementite, whilst the iron is called Ferrite. Cementite and ferrite may be regarded as forming a eutectiferous alloy system, the eutectoid point occurring at 0·89 per cent of carbon, at a temperature of 690° C. This eutectoid of ferrite and cementite is called Pearlite. A slowly cooled steel containing less than the eutectoid composition is shown by the microscope to consist of ferrite and pearlite; one containing more than 0·89 per cent of carbon to consist of pearlite and cementite; and one containing exactly 0·89 per cent of carbon to be entirely pearlitic. The ferrite-cementite system differs from the simple binary system in that pure iron exists in three allotropic forms, varying with temperature in regard to magnetic properties. The change from one modification to another is indicated by absorption of heat on heating, and evolution of heat on cooling. This causes arrests, or critical points on the heating and cooling curves, where time is plotted as the abscissa and temperature as the ordinate. On such a curve for a mild steel, shown in Fig. 3, containing 0·3 per cent of carbon, in addition to the transformation points of the iron, there is a marked arrest at 690° C., the temperature at which the pearlite separates on cooling.

These arrest points have received special names derived from their relative position counting from the ordinary temperature, and are Ac$_1$, Ac$_2$, and Ac$_3$ on heating, and Ar$_3$, Ar$_2$, temperatures at which the transformations occur on heating and cooling do not exactly coincide, the cooling curve always showing a slight lag. The temperatures indicated by the change or critical points are the criteria of the correct heat treatment of the steel. It must be borne in mind that the presence of alloying elements, such as manganese, nickel and chromium, has a profound effect on the position of these points on the temperature scale. Reference will be made to this in the paragraph on alloy steels.

If a plain carbon steel is heated to a temperature above its Ac_3 point, and held there for a short time, then cooled very suddenly by quenching in cold water, and examined microscopically after suitable etching, the structure observed is very different from that shown on slowly cooling the same steel. The structure observed gives some indication of the conditions obtaining at the temperature from which quenching occurred. In a plain carbon steel it is known that even with the most drastic quenching the cooling is not sufficiently rapid to suppress the transformations entirely. At temperatures above the Ac_3 point the steel consists of a solid solution of the cementite in the ferrite. This is called Austenite and is soft. Quenching a plain carbon steel fails to preserve the austenite. In its place appears a very hard constituent known as Martensite, which is not a true solid solution, but which is constrained to retain the carbide by the velocity of cooling. If the quenched steel is now reheated to a low temperature, the carbide begins to separate in a finely divided state and appears as a dark etching constituent, Troostite. This reheating is known as tempering. As the tempering temperature is raised, agglomeration of the carbide particles occurs. Martensite is very hard, and a martensitic steel is useless for structural work on account of its brittleness. As tempering proceeds, the tensile strength of the steel falls, but the elongation and shock-resisting values increase. The best combination of mechanical properties of a steel is obtained only when it has been correctly wrought, hardened and tempered.

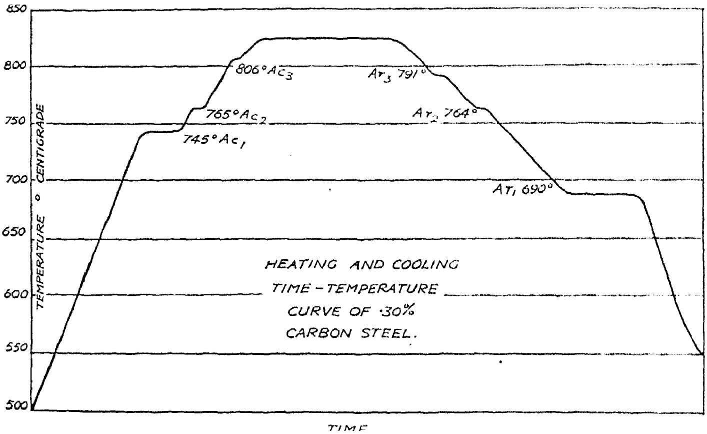

FIG. 3. TEMPERATURE-TIME COOLING CURVE OF A 0·30 PER CENT CARBON STEEL

When steel is cast in a large mass, the structure is relatively coarse. By forging or rolling, the original structure is replaced by a finer one, and this breaking down facilitates the solution of the constituents on reheating.

In all heat treatment of steel it is essential that the time for which the steel is held above the critical point, and the temperature attained above the critical point before quenching, shall be the minimum required to approach equilibrium conditions. The higher the temperature attained, the lower will the change points be on cooling. If either time or temperature should be excessive, the tendency is for the grain size to enlarge, with a consequent coarsening of the final structure.

It is generally accepted that a finer crystalline aggregate possesses tensile strength and toughness superior to a coarser aggregate on account of the greater resistance offered to cleavage and slip. With certain forgings, quenching and tempering are not practicable on account of the liability to fracture through strains due to uneven section, and normalizing is substituted. Normalizing means heating a steel (however previously treated) to a temperature exceeding its upper critical point by not more than 50° C., for about 15 min. and allowing it to cool freely in air. Castings are usually submitted to another kind of treatment—annealing. This removes casting strains and gives a more uniform structure. In this case the steel is maintained for a considerable time just above the upper critical point and allowed to cool very slowly.

An indication of the effect of quenching and tempering and normalizing on a 0·45 per cent carbon steel is given by the following figures.

Quenched in water from 870° C.

	Tempered at 200° C.	*Tempered at 600° C.*	*Normalized.*
Yield point . .	47 tons per sq. in.	36 tons per sq. in.	27 tons per sq. in
Ultimate stress .	65 ,, ,,	52 ,, ,,	44 ,, ,,
Elongation . .	18 per cent	25 per cent	27 per cent
Reduction of area .	33 ,, ,,	60 ,, ,,	54·5 ,, ,,
Izod impact value .	24 ft.-lb.	38 ft.-lb.	31 ft.-lb.

It will be seen from the above that, although the chemical composition remains unchanged, we have the material in conditions exhibiting marked differences in properties. The differences are more marked in high than in low carbon steels. This matter will be referred to later in dealing with welded fuselage construction, when the ductility is of great importance. A low carbon steel is then used so that there shall be no local hardening or cracking. Normalizing of such frameworks is impossible on account of their dimensions.

Alloy Steels. By the addition of other elements to plain carbon steels, some remarkable changes in physical properties are obtainable. In some instances one new element alone is introduced and in others, two, three, and even four are included for the steel to acquire the desired improved qualities. It has already been stated that the quenching of a plain carbon steel never results in the complete preservation of the austenite. One of the most marked effects of an added element on the iron-cementite system is its influence on the temperature of the critical points. For example, the presence of 13 per cent of manganese or 25 per cent of nickel increases the stability of austenite, or, in other words, depresses the Ar_3 point to such an extent that these two steels, even when slowly cooled, preserve an entirely austenitic structure. With certain nickel-chromium steels, air cooling produces a structure equivalent to a water-quenched carbon steel—i.e. martensite—and such steels are called "air hardening." They are particularly useful for the manufacture of such parts as would develop dangerously high internal stresses, or even fracture, when subjected to a drastic water quenching. Furthermore, the presence of the added elements is reflected in the increased tenacity without loss of ductility. Smaller amounts of these elements produce steels which, if sufficiently rapidly cooled by quenching in oil, give martensite and troostite by subsequent tempering.

With the chromium steels one effect is the change in the carbon content of the eutectoid composition, free carbide appearing at a much lower carbon content than in the simple system. This calls for exact control in manufacture and a thorough understanding of the correct heat treatment conditions.

Care must also be exercised in the choice of an alloy steel for its particular function in aircraft construction. One of the phenomena associated with the allotropic change which occurs in iron when a steel passes into the austenitic range is the loss of its magnetic properties. Austenite, whether preserved by quenching or by the presence of other elements, is non-magnetic and martensite is magnetic. For this reason, austenitic steels are sometimes used when non-magnetic material is essential. But although austenite persists down to normal temperature, the point at which it decomposes to martensite may occur at temperatures not much below normal, depending on the composition and the maximum temperature attained. This has a special significance if the non-magnetic austenitic steel is fitted in close proximity to the compass of an aircraft used under arctic conditions or high-altitude flight, and any formation of martensite may cause very erratic readings to be obtained. The change point of such a steel, therefore, should be well below the lowest temperature likely to be encountered in service.

Turning now to a general consideration of the alloy steels used in aircraft construction, these fall into two wide groups—the high tensile steels, and the non-corrodible steels. The high tensile steels contain as a rule about 0·2 to 0·4 per cent of carbon, about 3 per cent of nickel and 1 per cent of chromium, with the addition of small quantities of vanadium and molybdenum in certain specifications. These steels are particularly responsive to heat treatment, and can be treated to cover a remarkably wide range of properties, ranging from 50 to 100 tons tensile strength, with corresponding elongations. The presence of molybdenum is found to eliminate the condition of temper brittleness which occurs when these steels are tempered in a certain temperature range and slowly cooled. The nickel-chromium molybdenum steel, in addition to good all-round tensile properties, gives exceptionally fine impact test values, illustrating resistance to shock.

Nickel, alone, makes the structure of a steel finer, increases the strength, ductility and toughness, and also the ratio of elastic limit to ultimate stress.

Chromium, alone, increases the elastic limit and maximum stress without appreciable loss of ductility, and also the ratio of elastic limit to ultimate stress. A further benefit is the increase in hardness and resistance to shock and alternating stresses.

The nickel-chromium steels combine most of the good effects of the individual elements when added in the proportions quoted above. The non-corrodible steels are, again, nickel chromium steels, the one usually called "stainless" containing about 0·30 per cent carbon and 12 to 14 per cent chromium and up to 1 per cent nickel. It is essential that this steel should be correctly heat treated to acquire its stainless properties, when it is practically immune from corrosion. Failure to withstand corrosion can usually be traced to quenching from too low a temperature. The other type of non-corrodible steel contains about 0·15 per cent carbon, 6 to 8 per cent nickel, and 16 to 18 per cent chromium. It has an austenitic structure and is stainless in any condition. The austenitic condition, as already mentioned, is relatively soft, with the result that the elastic limit of this steel is approximately only 10 tons per square inch in the soft condition,[1] as against 30 tons per square inch for the lower nickel-chromium stainless steel, in the hardened and tempered condition. Cold rolled strip has a much higher elastic limit, and after shaping operations, parts must not be softened. This is an important point for the designer to remember. Since austenitic steels have a low elastic limit, they harden very readily, particularly on the surface, by cold work as the result of such operations as hammering, machining, and in some cases even by filing. Frequent annealing at 1,000° to 1,200° C. is required to remove this strain hardening, and rapid cooling gives a softer product. The work hardening of the austenitic stainless steels has been a serious hindrance to their fuller use. It is almost impossible to drill and tap small holes below $\frac{1}{4}$ in. diameter in them. When machining of any sort is necessary, it must be done rapidly and the cut should be continuous. A tool idling over the surface will inevitably harden it and make further work impossible without annealing.[2] But it must be remembered that after annealing the yield point is very low.

Reference has already been made to the possibility of setting up dangerous internal stresses by quenching, and the value of air-hardening and oil-hardening steels in reducing this liability. But even with these steels care must be taken to ensure that the heating is as uniform as possible. On heating a steel there is, first of all, the normal thermal expansion, and in addition there are volume changes associated with the allotropic and other change points, reversible on cooling. It is obvious that transference of heat takes time, and no matter how drastic the quenching, the outer skin must cool more rapidly than the centre of the mass. If the outer skin is cooled rapidly and becomes rigid, then the changes which occur within will set up internal stresses. These stresses when unavoidable can be reduced to a safe limit by low temperature annealing. The effect of the mass of the piece being treated must also be considered, as well as variations in section, in which stresses may cause distortion.

Normal failures in steel always occur across the grains when caused by steady loading or shock. This is a typical feature of this type of failure in all sound materials, and an intercrystalline fracture indicates some abnormality in the composition or condition of the metal. Failure under rapid alternating stress may expose the crystal faces upon which slip has occurred as a number of bright facets, which has led to the mistaken idea that alternating stresses cause the metal to "become crystalline," whereas the metal is always crystalline, and the appearance of the fracture depends on the mechanism of failure, which does not involve any change in the crystalline structure.

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[1] See D.T.D. Specification 176 (Chapter X).

[2] See *Aeroplane*, 29th April, 1931: "The machining of Stainless Steel," by Waddell and Worton.

Lastly, the question of machined surface should be mentioned. It is more than æsthetic taste which is satisfied with a polished finish. In all but low carbon steels it is a necessity. The discontinuities and unevenness of a rough surface set up local stresses, serve as penetration points for corrosion, and by severe concentration and localization of stresses may initiate cracks which will develop through the material, particularly when it is subject to vibration. Dr. Rosenhain states: "I would rather have the poorest of our spring steels with a ground and polished surface than a roughly finished spring plate of the best alloy that money can buy." [1]

Aluminium. Aluminium is one of the most abundant and widely distributed of elements. Though it is never found in the free state, it occurs as a silicate in the different clays, as an oxide in corundum, ruby and sapphire, as a compound silicate in the various felspars, as a double fluoride with sodium in cryolite, and as a hydrated oxide associated with iron in bauxite. It was unknown as a free metal until a hundred years ago, and the present methods of manufacture began their development less than fifty years ago. At that time the cost was excessive, but the increasing demand which resulted from a realization of its remarkable properties has led to improved methods and a great reduction in price.

Though compounds of aluminium form so large a part of the earth's crust, the only one which is commercially workable is bauxite (Al_2O_3, H_2O). This mineral is found in Germany, Austria, France, Northern Ireland, the United States, and British Guiana.

The first stage of the manufacturing process is to clear the ore of impurities and reduce the hydrated oxide to alumina (Al_2O_3).

The alumina is then fused in an electric furnace either alone or in the presence of cryolite. The furnace is a carbon-lined steel shell with negative pole at the bottom. The positive pole is a carbon rod or rods which project downwards into the fused mass. The aluminium oxide is decomposed, the oxygen escaping at the top and the aluminium collecting round the cathode at the bottom, from whence it is drawn through a tap hole. Owing to the large amount of electric power required, aluminium is usually manufactured in places where water is plentiful and the power cheap. Those in Great Britain are situated at Foyers in Scotland and at Dolgarrog. Our principal supplies of the ore come from British Guiana and Ireland.

Aluminium is a comparatively weak but ductile and malleable metal whose principal virtues are its lightness, appearance, adaptability and affinity for alloying with other elements for different purposes. The specific gravity is 2·58 to 2·7. Owing to its low tensile strength, it is not used in the main structural members of aircraft. It is, however, an extremely valuable material for such secondary parts as cowlings, fairings, tanks, etc., and is easily beaten into curved panels. It may be cast or machined to make distance pieces, packing blocks, and in the form of extruded and drawn sections it is used for window frames, door steps and cockpit edge beadings. Welding is easily carried out on aluminium sheets, and is used when tanks or cowlings are made from this material.

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[1] *Journ. R.Ae.S.*, August, 1930: "The Development of Materials for Aircraft Purposes," by Rosenhain.

More used and useful than aluminium itself are its alloys. The best known of these is made to B.S. Specifications L1 (bar), L3 (sheet) and T4 (tube). This alloy contains 3·5 to 4·5 per cent of copper, 0·4 to 0·7 per cent each of manganese and magnesium, and 0·3 to 0·6 per cent of silicon. It is usually sold under the trade names of "Duralumin" and 17ST. Though its specific gravity is only 2·85, it has a tensile strength of 25 to 26 tons per square inch when in the hard condition, a strength almost equal to that of mild steel.

Copper forms a compound with aluminium to the formula $CuAl_2$, and this, together with magnesium silicide, Mg_2Si, hardens and increases the tensile strength of aluminium. Their effect is similar to that of carbon on steel. When raised to a temperature of over 475° C., these compounds dissolve in the aluminium. If now it is quenched in cold water they are retained in solution at atmospheric temperatures. The material is in a soft condition. But it is not in their nature to remain so dissolved, and gradually they are precipitated in a very finely divided state. This process is apparent in the age-hardening which takes place in aluminium alloys. It lasts with decreasing intensity during several days, the greatest difference being noticed in the first few hours.

Raising duralumin to a lower temperature of about 360° C., followed either by air cooling or quenching, softens the material almost permanently and renders it easy to work and shape.

These two processes are known respectively as "Heat Treatment" and "Annealing." They are described in their practical form in Chapter VII.

In common with most other metals, duralumin is subject to corrosion, particularly in salt water spray. Though there have been scares on this account, the trouble does not appear to be greater than that experienced with other materials if suitable precautions are taken. The usual method in this country is known as anodic treatment, and consists of depositing electrically on the surface a thin film of aluminium oxide, after which it is greased with lanoline and painted or varnished.

Owing to the more finely divided state of the copper compound and magnesium silicide when the material has been fully heat-treated and quenched, corrosion is less potent then than after annealing. The more effective the quenching, the more resistant is the surface. The principles and methods of anodic treatment are given in Chapter VIII.

A newer material which has been developed from Specification L3 is "Alclad" Sheet and Strip. This has a high resistance to salt water and alkaline attack owing to its being surfaced on both sides with pure aluminium. These surfaces merge almost imperceptibly into the alloy and cannot peel off. The aluminium, which is of a 99·75 per cent purity, is much less liable to corrosion than the alloy which it protects, and scratches are said to heal up. Moreover, the surfaces, being much more ductile than the core, do not crack in the same way as the unsurfaced metal may. The treatments of annealing and normalizing are carried out in the ordinary way, but anodizing is unnecessary unless the corrosive conditions are liable to be severe. "Alclad" alloy can be pulled through a draw bench more easily than duralumin as the soft surface acts almost as a lubricant. Its strength is slightly less than that of L3 of the same overall thickness, since about 10 per cent of this thickness is a weaker material. The British Standard Specification for it is L.38.

Another material which shows considerable promise is M.G.7,[1] as it is known commercially. This differs from the previous wrought aluminium alloys in containing 5 per cent to 7 per cent of magnesium. The specific gravity is only 2·63 compared with 2·85 for duralumin. It is supplied in the extruded, rolled, and forged forms. Sheet and strip may be drawn or rolled in the same way as other aluminium alloys, but no final heat treatment is necessary. It develops its full strength without this, unless it has been annealed for some particularly intricate work. The material resists inter-crystalline corrosion and no protective treatment is therefore necessary. With certain limitations it may be welded and the weld, particularly if hammered, may develop 80 per cent of the original strength. The Air Ministry has approved M.G. 7 sheet in two forms. The first made to D.T.D. Specification 177 is in the hard condition, and the second D.T.D. 182 is annealed. The material has other specification numbers for bars, tubes, and rivets.

Aluminium alloy bar to B.S. Specification No. L1 machines well and can be forged and used for drop stampings. The forging temperature is about 420° C. After either machining or forging, the material must be heat treated, and anodizing is recommended as a protection on very thin sections which are severely exposed.

The "Hiduminium R.R. 56" alloy is made to B.S. Specification L40. This is now being used for many kinds of stampings, from small link mechanisms to airscrew blades. It is more consistent in its strength and the yield point is higher than in most light alloy forgings.

"R.R. 56" is now being extruded in the form of tubes, angle, channel and Tee sections. It can be used for the same purposes as duralumin and 17 ST made to Specifications 4 L1, 3L3, and 3 T4. It has the advantage of being slightly lighter for the same strength. With a specific gravity of 2·75 it has an ultimate tensile strength of 27 tons per square inch. The heat treatment is different from that of duralumin, owing to its different chemical composition. R.R. 56 should first be heated to 520°–535° C. and quenched in water. The second stage of the process, known as the "precipitation" or "ageing treatment" is to heat the material to 165°–175° C. for 10 to 20 hours and then leave it to cool in air. If the temperature control is correct within fine limits it may instead be heated to 195°–205° C. for two hours. This alloy does not "age-harden" at atmospheric temperatures like the other strong aluminium alloys. Shaping operations may be carried out after quenching, but there is no time limit before the final precipitation treatment. If R.R. 56 is bought from the manufacturers, not in strip form, but extruded to the final cross section (see next page), the amount of cold work necessary is very much reduced. Three other "Hiduminium" alloys are known as R.R. 50, R.R. 53 and R.R. 53C. These are casting alloys and may be either sand cast or chill cast. Their Air Ministry Specifications are respectively D.T.D. 133B, D.T.D. 131A, and D.T.D. 309. R.R. 50 has an ultimate tensile strength of 10 to 16 tons per square inch, whilst R.R. 53 gives 14 to 25 tons per square inch, depending on the method of casting and the heat treatment.

[1] See "Light Alloys for Aeronautical Purposes, with Special Reference to Magnesium," Dr. L. Aitchison, Royal Aeronautical Society Lecture, 14th December, 1933.

The range of constituents of the "Hiduminium" group is as follows—

Copper	0·50 to 5·00 per cent
Nickel	0·20 ,, 2·50 ,,
Magnesium	0·05 ,, 5·00 ,,
Iron	0·60 ,, 1·50 ,,
Titanium	0·05 ,, 0·50 ,,
Silicon	0·20 ,, 0·50 ,,
Aluminium	remainder.

The actual constitutions of the individual alloys are given in Chapter X.

The titanium is added as a cleanser and to prevent oxidation of the metal as it is being poured. Another range of aluminium alloys of somewhat similar analysis but with cerium substituted for titanium is sold under the trade name of "Ceralumin." In addition to giving good foundry properties, it is claimed for the cerium that "it allows the beneficial mechanical effects of a high iron content to be obtained by suppressing the embrittling aluminium-iron constituent which is otherwise liable to be formed."

"Ceralumin" has a specific gravity of 2·79 and as sand cast toSpecification D.T.D. 255 it has a maximum strength of 18 tons per square inch. The heat treatment of such castings is in two stages like that of the Hiduminium alloys. It is first heated for four to six hours at 515°–535° C. and quenched in oil or water. It is then heated to 170°–180° C. for 16 hours and quenched or air cooled. If, however, instead of the second stage the material were allowed to age-harden at room temperature for six days it would be softer and more malleable. This softer form is covered by Specification D.T.D. 250. Like "Duralumin" and "Hiduminium," "Ceralumin" is also made for extrusion, a process which is becoming increasingly popular.

In the extrusion process, metal heated to a plastic state is forced through dies by means of hydraulic pressure. Sections, such as angles, channels and tees, are thus produced having a smooth surface and a fine uniform structure.

The permissible thickness of the extrusion varies according to the section, but sections which could be inscribed in a 4-in. diameter circle, down to ⅛ in. thick and up to 20 ft. long, are commonly produced. These are not, however, the limits of what is possible, and the process is being increasingly used by alloy manufacturers to save the aircraft constructor many of his workshop difficulties.

Two of the best known casting alloys are made to B.S. Specifications L5 and L33. They are of little strength, but extremely useful for packings and many unstressed fittings. L33 welds easily to aluminium and is often used for screwed fittings on tanks of that material.

There are also other aluminium alloys used for casting, including the well-known Y-alloy, but they are more used in aircraft engine work than in the construction of the machine itself.

Magnesium. Magnesium is, like aluminium, an element very widely distributed in the earth's crust. It exists in the form of silicate, carbonate and chloride in such minerals as hornblende, talc, asbestos, meerschaum, dolomite, magnesite, carnallite and olivine.

Metallic magnesium was first produced by Sir Humphry Davy in 1808, some sixteen years before the isolation of metallic aluminium. It was not, however, until 1900 that a commercial process for extracting it from its ores was evolved. This was the electrolytic method developed in Germany. But magnesium at that time had few applications beyond its use in photographic work and in pyrotechnics.

Three years later the first alloy was produced in Germany, and in 1909 "Elektron" was exhibited there. The latter is now the best known series of the magnesium alloys. Manufacture did not proceed on a commercial basis until 1914, when the urgent needs of war and the shortage of aluminium alloys and brass in Germany gave a great impetus to magnesium research. Since then many developments have taken place and the material is definitely reaching an important position in engineering practice.

The present-day methods of manufacture are not made known, but they are a development of an earlier one in Germany whereby fused carnallite was electrolyzed, carnallite being the mineral chlorides of magnesium and potassium. In America, magnesium was made from pure magnesia (MgO) by adding it to a bath of fused magnesium and potassium chlorides, the metal collecting at the negative electrode.

The specific gravity of pure magnesium is 1·74, and that of elektron, which also contains small quantities of aluminium, manganese, zinc, copper and silicon in alloy, is 1·82. This figure is so strikingly below that of any other commercial metal that the material should make a great appeal. Even duralumin, with a specific gravity of about 2·85, is more than 50 per cent heavier than magnesium. With this low specific gravity, it has a comparatively high tensile strength, so that its strength density ratio is 10 against 8·8 for duralumin. But there have been great difficulties with the metal, such as its liability to fire, its poor resistance to corrosion, and its high cost of manufacture. These, it is claimed, have now been overcome in elektron alloys. If the troubles can be further eliminated it is extremely likely that elektron will become a rival to duralumin and high tensile steel even for main planes and fuselage structures. Elektron is approved by the Air Ministry with varying quantities of alloying metals under Specifications D.T.D. 118 as sheet, D.T.D. 142 and 259 as bar and extrusions, and D.T.D. 136A, and 140A as castings.

The physical properties of these alloys vary with the constituents, and the ultimate tensile strengths range from 11 to 20 tons per square inch in the sheet and bar forms.[1] They may be graded into two groups, the first having the high tensile strength of 18 tons per square inch. The second group with the lower strength may be easily welded and is more resistant to corrosion. Oxy-acetylene welds in this sheet (D.T.D. 118) may be as reliable and easy to make as those in mild steel, and the strength is 80 to 90 per cent of that of the unwelded sheet. Even when worked in as thin sheets as 26 s.w.g. there appears to be no tendency to flare up in the welding flame. The material is protected against corrosion by treatment in dichromate solutions, the process being known as "chromating." This, like the anodic coating on duralumin, serves as an excellent base for a paint varnish or enamel finish. Elektron tanks have shown no signs of corrosion after two years' commercial service. This process is described on a later page.

The technique of working elektron is different from that used for either steel or duralumin. When cold only slight deformation is possible, and any shaping which is achieved may suffer from severe internal stresses. Any considerable amount of work must be carried out at a temperature of about 250° C. In beating tank and fairing shapes, a blow-lamp playing on the surface is usually sufficient, if the radius of bend is, as it should be, large. Unlike steel and aluminium alloys, heat treatment subsequent to working is unnecessary.

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[1] See Chapter X for Strength Tables and Specifications.

Rapid changes of section and concentration of stress are to be avoided.

In addition to sheet and bar, elektron is now being supplied in the excluded form in a variety of shapes and sizes.

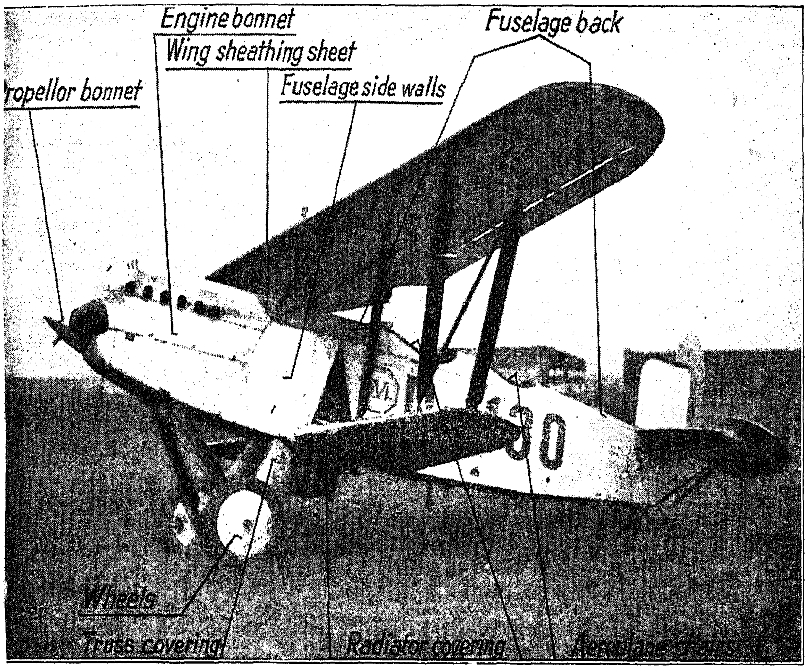

FIG. 4. ALBATROS BIPLANE

Uses of magnesium alloys in aircraft structures

(By courtesy of Messrs. F. A. Hughes & Co., Ltd.)

It machines very easily and gives a clean, silver-bright finish without any signs of the "drag" shown in aluminium and its alloys.

Sufficient has been said, perhaps, to show that elektron may be considered seriously by aircraft constructors and that rapid advances have been and are being made in its development. Fig. 4 illustrates the parts of an Albatros biplane which were made in elektron. After about a year's use, when the machine was put out of service, these parts were still in perfect condition.

NICKEL ALLOYS. **Inconel.** Inconel is composed approximately of 80 per cent nickel, 14 per cent chromium and 6 per cent iron, and can be work hardened to raise the tensile strength from 35–50 tons per square inch to 85 tons per square inch. In view of its particularly high resistance to heat oxidation at very high temperatures it finds a ready use in the manufacture of silencers and exhaust manifolds. In this application benefit will also be derived from its low coefficient of expansion, this becoming apparent both in the actual fabrication and in the working life of such parts. Inconel also offers good resistance to the corrosive action of the various chemical compounds deposited on the insides of exhaust manifolds, particularly on engines operated on anti-knock fuels.

Various methods of joining Inconel are possible, including riveting, soldering, brazing and welding.

Inconel sheet and strip are covered by Specification D.T.D. 328.

"K" Monel. This may be used to advantage where high strength and/or hardness properties are required, combined with high corrosion resistance or immunity from rusting. Advantage is found in its non-magnetic qualities.

It is a development from the well-known Monel metal, a high nickel-copper alloy, being basically of the same chemical composition, with the addition of aluminium. Heat treatment renders it soft or hard and strong, at will, and it is readily workable, either cold or hot. In its cold-worked and thermally hardened condition may be found its highest ultimate tensile strength of 72 tons per square inch with a corresponding Brinell figure of 320.

With good quality high-speed steel tools, "K" Monel has similar machining characteristics to mild steel, though in the work-hardened plus thermally-hardened condition, Widia or similar tools will be necessary. Machining before final thermal hardening obviates the necessity for special tools.

The original Monel metal alloy is covered by A.M. Specification D.T.D. 204, covering rods, wire and rivets.

COMPARISON AND CHOICE OF MATERIALS

Three main groups of metals have been discussed as coming within the scope of the aircraft constructor for structural purposes. They are—

1. Carbon and alloy steels.
2. Aluminium and its alloys.
3. Magnesium alloys.

Each of these groups covers a wide field, particularly the first, which has been shown to range from mild steel with a tensile strength of the order of 30 tons per square inch to alloy and high carbon steels with a tensile strength of 100 tons per square inch and over. Aluminium alloys are produced in fewer yet very diverse forms. Magnesium alloys can barely be said to have any hold at present, except for secondary structure, but they are thought to have a big future.

How is the designer to choose amongst all these materials? The very diversity found in aircraft structure proves the difficulty of the choice. A superficial comparison is not sufficient.

The factors which influence any selection may be classified briefly as follows—

1. Strength considered in relation to weight, "strength" being the figure appropriate to the function of the particular member—e.g. tensile or proof stress for ties, compression yield or modulus of elasticity for struts, etc.

2. Physical properties.
   (*a*) Durability and resistance to wear, service, fatigue, etc.
   (*b*) Resistance to corrosion, including a consideration of cost of protection.
   (*c*) Working properties, taking into account elaborate equipment, heat treatment, etc.
3. Cost.
   (*a*) Cost of the raw material.
   (*b*) Cost of working, wages of the appropriate labour, labour and tools available.
4. Availability and sources of supplies.
   (*a*) Size and regularity of supplies.
   (*b*) Consideration of supplies required in time of war and the possible place of such war.

Some of these factors, particularly in the first and second categories are constants which do not vary. Others, such as cost, vary both in time and place. Others, again, may be influenced by further research and development if the expense appears to be justified. This, from the constructor's point of view, applies particularly to tools and working methods.

It is not sufficient to consider these points in relation to aircraft as a whole. They must be considered in relation to each particular design and almost to the individual members in the design. Resistance to wear and service, for example, is not so important in a military fighter as in a commercial freight carrier. And the material which is thought to be most suitable for a main plane spar is not necessarily the best for an undercarriage axle or a flying boat hull.

The complexity of the problem has been rather stressed on account of the tendency in some quarters to make light of it. Up to a point the materials may be weeded out on a strength for weight basis, but even at this stage the less theoretical points must be borne in mind.

Considering first the strength in relation to the weight, a useful ratio is obtained by dividing the proof stress by the specific gravity.[1] Taking a number of well-known materials—

This ratio may be easily tabulated for all the materials listed in the Specifications (Chapter X). Rearranging this table in order of merit

	Mild Steel Sheet, S3	High Tensile Steel Sheet, S86	High Tensile Steel Strip, D.T.D. 138	Non-corrodible Steel Sheet, D.T.D. 166A	Duralumin Sheet, L3	Elektron Sheet, D.T.D. 120
Proof stress in tons/sq. in.	20	42	65	40	15	7
Specific gravity	7·8	7·8	7·8	7·8	2·85	1·82
Proof stress/sp. gr.	2·56	5·38	8·32	5·13	5·26	3·86

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[1] Proof stress is defined as that stress at which the stress-strain diagram departs from the straight line of proportionality by 0·1 per cent of the original gauge length. It is a figure which can be determined more exactly than yield point, and it is more useful than ultimate tensile stress, particularly in some of the "plastic" steels. A proof stress of 0·5 per cent extension is occasionally used for non-ferrous materials, and is specified as such.

and giving D.T.D. 138 the value of 1 for the purposes of comparing their qualities purely as tie members, we get—

High Tensile Steel Strip	D.T.D. 138	1
High Tensile Steel Sheet	S86	1·54
Duralumin Sheet	L3	1·58
Non-corrodible Steel Sheet	D.T.D. 166A	1·62
Elektron Sheet	D.T.D. 120	2·15
Mild Steel Sheet	S3	3·24

Mild steel would appear to be completely ruled out as an economical material to take tension. Tie rods are normally made of high tensile steel, as this table indicates. The general use of mild steel in lugs and fittings under tensile loads may be explained by considerations of cost, working qualities, etc.

Turning from ties to struts, the position is more complicated. Short struts fail by pure compression, the compressive yield point being the measure of their strength. Long or Euler struts, on the other hand, fail by bending, the modulus of elasticity being the criterion. Intermediate cases are influenced by both yield point and elasticity. And all may be affected by secondary buckling if the strut wall is thin.

Taking yield point first and comparing some much used tubes—

	Carbon Steel Tube, T1	Axle Tube, T2	50-ton Carbon Steel Tube, T50	Mild Steel Tube, T26	Welding Tube, T45	Duralumin Tube, T4
Yield point in tons per sq. in.	30	78	40	11	40	18
Specific gravity	7·8	7·8	7·8	7·8	7·8	2·85
Yield/Sp. Gr.	3·85	10	5·13	1·41	5·13	6·32

The long strut, designed on the modulus of elasticity, E, gives—

	Carbon Steel Tube, T1	Axle Tube, T2	50-ton Carbon Steel Tube, T50	Mild Steel Tube, T26	Welding Tube, T45	Duralumin Tube, T4
Modulus of elasticity/10^6	30	28·7	30	30	30	10·5
Specific gravity	7·8	7·8	7·8	7·8	7·8	2·85
Mod. El./Sp. Gr.	3·85	3·68	3·85	3·85	3·85	3·68

The order of merit is—

	Short Struts	*Long Struts*
Axle Tube, T2	1	1·04
Dural Tube, T4	1·58	1·04
50 Ton Carbon Steel Tube, T50	1·95	1
Welding Tube, T45	1·95	1
Carbon Steel Tube, T1	2·6	1
Mild Steel Tube, T26	7·1	1

The normal strut used in an aircraft structure lies somewhere between these two limits. It will be seen that the mild steel tube, so poor in direct compression, may have considerable justification in actual practice, especially when its cost is taken into account. In order to make the comparison fairer, the full yield point of the welding tube was used, not the reduced yield point which results from welding. Welding, of course, has no effect on the modulus of elasticity. Using the reduced yield point would only have been justified if the work and weight of machined end fittings had been brought into the calculation for the other tubes, obviously an impossible procedure. Treatment on these lines might be extended to include torsion members, bolts under shear, and so forth. It is easily done, but the limitations of the method have been pointed out.

The maximum permissible stress in a simple beam is usually taken as the mean of the ultimate tensile stress and the proof stress, but this, as a basis of comparison, is even more unsatisfactory than in the cases given above; for although it may be possible to design a beam of great strength in high tensile steel, no method has been found of increasing Young's Modulus (E). The value of this ratio remains approximately the same at 30×10^6 lb. per square inch for all steels. Thus, whilst the failing strength of a beam is a function of the mean of the ultimate and proof stresses, the deflection is not. Other things being equal and ignoring shear, deflection is a function of E. Imagine two beams of equal dimensions, methods of support and loading, the one made of mild steel and the other of high tensile steel. Load for load they will deflect the same amount until the mild steel one collapses. The other will then go on deflecting until at a much greater load and, after much more deflection, it too will collapse. But for a given load, the second would not be made as heavy as the first. The outside dimensions or the thickness of the material would be reduced. In thus taking advantage of the greater strength of the material, the moment of inertia would be reduced. The deflection of the high tensile steel beam would then be even greater. Putting it in formula: $\delta = \frac{KWL^n}{EI}$ where K and ^{n} depend on the methods of support and loading. It will be seen that neither ultimate nor proof stresses enter into this equation in even a disguised form.

For structures of normal proportions Young's modulus imposes a limit on the use of steels of high tensile strength, and it appears likely that such improvements as are made in steels will be rather in the direction of improving their working and stainless properties than in pushing up the ultimate strength.

The following materials are in general use in this country for the purposes stated—

(For the qualities and meanings of the following Specification numbers see Chapter X. In all cases the latest issue number is implied Those in heavy type are non-corrosive or stainless steels.)

Wing Structures.

(*a*) ALUMINIUM ALLOY WINGS

Spars	. L3, L38 or L40
Ribs . .	. T4, L3, L38 or L40
Struts . .	. L3, L38, T4 or T50.
Bracings, Internal	. W1 or W8.
Bracings, External	. W3.
Fittings, Sheet .	. S4, **D.T.D. 60A.**
Fittings, Bar .	. S1, S2, **S80.**

L38 (Alclad) is slightly more expensive than duralumin, L3, in first cost, but there is a saving on anodic treatment. For ribs, duralumin tube, T4, is more expensive than alclad or duralumin strip, but may not be obtainable readily in the required sizes. There is, however, less workshop expense as it is already in shape. Similarly with struts, solid-drawn tubes either in duralumin, T4, or steel, T50, may save working costs, but require a fairing to be added if they are external.

(*b*) STEEL STRIP WINGS.

Spars Ribs	H.T. Strip	S86, S87, S88, D.T.D. 137, 138.
	Stainless H.T. Strip	**D.T.D. 46A, 60A, 166A.**
Struts . .		T50 or built-up from one of above strip steels.
Bracings, Internal		W1 or W8.
Bracings, External		W3.
Fittings, Sheet		S4, **D.T.D. 60A, 166A.**
Fittings, Bar .		S2, **S80.**

The choice of strip is large, as each firm specializing in this type of construction has developed its own materials.

(*c*) FUSELAGES.

Monocoque—

Frames and Shell	L3, L38 or L40.
Fittings, Sheet	S4, **D.T.D. 60A, 166A.**
Fittings, Bar.	S2, **S80,** L1.

Welded Structure—

Longerons, etc. .	D.T.D. 41, T35, T45.
Fittings, Sheet .	S3.
Fittings, Bar .	S1, S21.[1]
Bracings . .	W1, W8.

Tubular structures with mechanical joints—

(i) Light alloy—

Longerons, etc.	T4, D.T.D.220.
Fittings, Sheet	L3, L38, S4, **D.T.D. 60A, 166A.**
Fittings, Bar .	L1, S2, **S80.**
Bracings .	W1, W8.

(ii) Steel—

Longerons, etc.	T50, T45, T35, **D.T.D. 105.**
Fittings, Sheet	S3, S4, **D.T.D. 60A, 166A.**
Fittings, Bar .	S1, S2, S6, **S80.**
Bracings .	W1, W8.

Steel strip structure—As for steel strip wings.

(*d*) FLYING BOAT HULLS, FLOATS, ETC.

Frames and Shell .	L3, L38, L40.
Fittings, Sheet . .	L3, **D.T.D. 60A, 166A.**
Fittings, Bar . .	L1, **S80.**

(*e*) TAIL UNIT.

(i) Light alloy—As for main planes.
(ii) Steel strip—As for main planes.
(iii) Welded—

Spar and Ribs	T45, T35, D.T.D. 41.
Fittings, Sheet	S3.
Fittings, Bar	S1, S21.[1]
Bracings, Internal	W1, W8.
Bracings, External	W3.

(*f*) UNDERCARRIAGE.

Axle	T2, D.T.D. 254.
Radius Rod	T1, T50, T35.
Compression Leg	T1, T50, T45.
Fittings, Sheet	S3 for welding, S4, **D.T.D. 60A, 166A.**
Fittings, Bar	S1, S2, **S80.**

(*g*) ENGINE MOUNTINGS.

Welded—

Tubes	D.T.D. 41, T45.
Fittings, Sheet	S3.
Fittings, Bar	S1, S21.[1]

Jointed—

Tubes	T1, T50, T45.
Fittings, Sheet	S3, S4.
Fittings, Bar.	S1, S2.

(*h*) CONTROLS.

Cables	W2.
Levers and Fittings—	
Sheet	S3, L3
Bar	S1, S21, L40.
Tubes	T4, T1, T26, T35, D.T.D. 41.

(*j*) TANKS.

Tinned Steel—

Shell	S20.
Fittings, Sheet	S3, S20.
Fittings, Bar	B6, B13.

Aluminium—

Shell	L4, L16.
Fittings	L5, L33.

Magnesium—

Shell	D.T.D. 118.
Fittings	D.T.D. 142.
Tank Straps	L3 or scrap from any available H.T-steel scrap.

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[1] S1 may be used for small fittings, but S21 should be specified for anything over 1¼ in. diameter if normalizing cannot be carried out.

Thus tabulated, the available materials appear a little less formidable than the complete list of specifications. The first choice to be made, of course, is the material for the primary structure, the remainder following from that. In a plant specializing in marine aircraft, where aluminium alloy is largely used in the hulls, one would not find separate equipment to produce wings in strip steel. There is economy in consistency, and the remainder of the structure—wings, tail unit, etc.—would be built in duralumin or alclad too. Similarly, a welded tail unit and engine mounting goes with a welded fuselage. A strip steel fuselage implies strip steel wings and tail. In this way duplication of equipment is avoided and overhead charges reduced.

New materials are constantly being added to the list, and many more are to be expected, ferrous and non-ferrous.[1] High tensile alloys steels are scarcely less in their infancy than aluminium alloys, or, for that matter, magnesium alloys. There are great possibilities, and the aircraft constructor waits for the metallurgist. Entirely new materials may yet be discovered. Beryllium, with even greater possibilities than magnesium, is still almost unknown beyond the laboratory. Details of design depend on the metal used, and developments in the one will keep pace with those in the other.

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[1] See *Journ. R.Ae.S.*, August, 1930, "The Development of Materials for Aircraft Purposes," Rosenhain, also *Journ. R.Ae.S.*, November, 1938, "Materials of Aircraft Construction," Gough.

CHAPTER III

MAIN PLANES AND MAIN PLANE STRUCTURES

MAIN Plane Construction will be treated under the two main headings of Biplane and Monoplane. Before dealing with the details, the present position will be reviewed and the two extreme cases of the fabric covered biplane and metal-clad cantilever monoplane discussed in general terms.

A conventional type of wing structure for biplanes was evolved and used almost universally for many years, irrespective of the material —wood, steel, or duralumin. This type of structure was for planes of rectangular plan form, and a section of constant depth from the centre to within a short distance of the tip. The air load was taken on a fabric covering which transmitted it to ribs of braced girder construction. These carried the load to two spars at about one-quarter and two-thirds of the chord from the leading edge. The spars were beams supported and separated by interplane struts, which divided their lengths into two or more bays. The transverse and longitudinal panels thus formed were cross braced with high tensile wires.

The centre of pressure lies between the spars in normal flight, and in stressing the load is divided between them in inverse ratio to the distance of the C.P. from each. This stressing method assumes that the two trusses, front and rear, are free to deflect independently of each other and that they are not restrained either by the ribs or by the incidence bracing.

The spars were, however, assumed to act together in taking drag and the horizontal components due to staggered interplane struts. For this purpose, and also because the spars were weaker under bending in the horizontal direction, struts were run between them, forming rectangular panels in plan view; these panels being also cross-braced with wires.

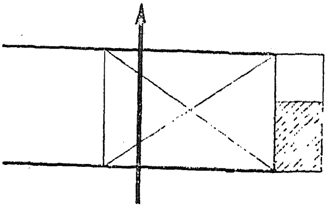
A structure of this kind is light and no great improvement has been made on it for the biplane. Even in turning over to metal construction, no change occurred and each wooden member was merely replaced by a metal one.

Many monoplanes, particularly in the high wing and parasol arrangements, have also been built in this way. Constructionally, if not aerodynamically, it is as if the lower plane had been removed and the vertical interplane struts replaced by lift struts sloping down to the lower longerons. But aerodynamic design has developed with structural design and at the other end of the scale from the thin rectangular biplane wing there is now the cantilever monoplane with a taper in both plan form and thickness, the section at the root, in some cases, having twice the thickness: chord ratio of the biplane.

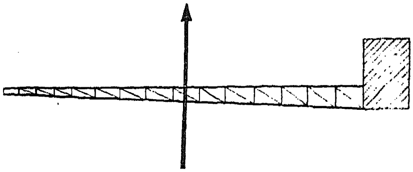
Compare the biplane and monoplane and consider only simple vertical load on one of the trusses (Fig. 5). Owing to its bigger span, the very much narrower base and the lack of external bracing, the cantilever carries much bigger loads at its root than are taken in the upper and lower spars of the biplane; but against this, there is no axial end load, and the bending moment curve of the monoplane shows a simple increase from tip to root and has no alternating maxima and minima.

In the monoplane, therefore, it is easier to develop a uniform stress and use the material economically. The taper in depth helps in achieving this economy.

It was stated above that, in the biplane, a stressing assumption was made that the front and rear trusses deflected independently and were not restrained by the ribs or incidence bracing. Such an assumption may not depart dangerously far from the truth, particularly as the section is thin; but in the monoplane, it is less justified owing to the depth of the section, and the question of torsion must be investigated.



BIPLANE TRUSS



CANTILEVER MONOPLANE TRUSS.

Fig. 5

It is a common practice to carry some of this torsion in a metal skin covering of the upper and lower surfaces.

Consider an elementary cantilever wing in the form of a rectangular cell (Fig. 6) encastre at one end. The cell will have a flexural axis, which may be defined as a lateral line O_1–O_2 such that when vertical load is applied anywhere along its length, only vertical bending will occur; but there is only one position of the centre of pressure which can coincide with this line. In all other positions there will be a torsional as well as a translational deflection.

Let P represent a load in the section $ABCD$, not passing through the flexural axis O_1–O_2. At O_1 apply two equal and opposite forces P_1 and P_2, each equal and parallel to P. These equilibrate and the cell is now under the action of the direct force P_2, causing vertical deflection and the couple of P and P_1, causing rotational deflection.

Considering first only the rotational case: the top, bottom, and side panels will be in shear as shown by the direction of the arrows. In the anel $BCC'B'$, for example, there will be tension along the line CB'

and compression along the line BC'. This will cause a wave to develop from C to B' with shallower ripples parallel to it. Similar waves and ripples will develop simultaneously in the other panels.

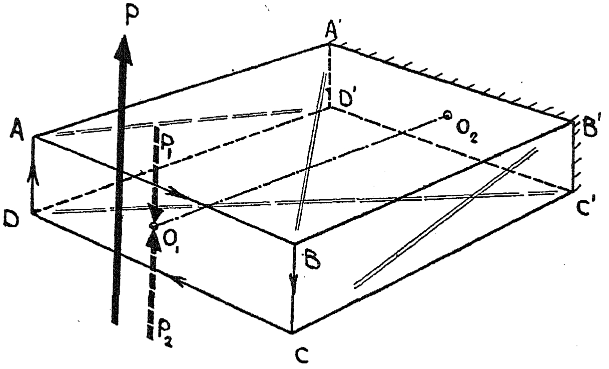


FIG. 6

Secondly, the effect of the vertical load P_2 will be to augment the shear in $ADD'A'$ and relieve it in $BCC'B'$.

Add a number of such cells to one another, camber the top and bottom surfaces, fit leading and trailing edges, and a structure appears which resembles, in principle, some of the cantilever wings described in the second half of this chapter.[1]

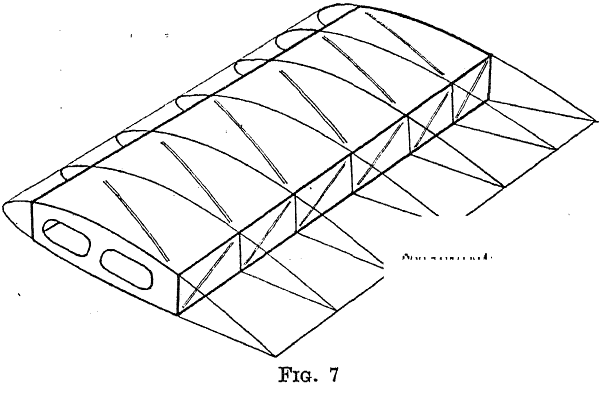


FIG. 7

There is a centre trunk with diaphragms at intervals. The front and rear walls are spars to take the vertical bending. The top and bottom surfaces assist in resisting the torsion.

In some cases the surfaces are stiffened with corrugations in the longitudinal direction. The effect of these on a panel in shear is to prevent the formation of diagonal waves, and it is characteristic of them that when collapse eventually occurs it is sudden and definite. There is less deformation than in the flat panel, but provided that the elastic limit is not passed, the waves in the latter will disappear on releasing the load and their presence does not necessarily indicate imminent collapse.

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[1] The author is indebted to a paper " Problemi moderni nella construzione metallica degli aeroplani," by G. Gabrielli, in *L'Aerotecnica,* January, 1931. See also R. & M. No. 1553, "Summary of the Present State of Knowledge regarding Sheet Metal Construction," by H. L. Cox, also "Some Developments in Aircraft Construction," H. J. Pollard, *Journ. R.Ae.S.*, July, 1934.

In some monoplane wing structures, the metal skin extends from leading to trailing edge and there is more than one spar (e.g. Junkers, p. 143). In another, the trunk is not rectangular (Kellner-Bechereau, p. 138). In the Breda (p. 148) the spars are brought close together and braced with struts to form a girder strong in both bending and torsion. In the Dewoitine (p. 125) there is only one spar, and the torsion is taken by the leading edge. The Monospar is also a single-spar wing, and the torsion bracing consists of pyramids of wires on each side, forming a double helix (p. 92). This wing is fabric covered.

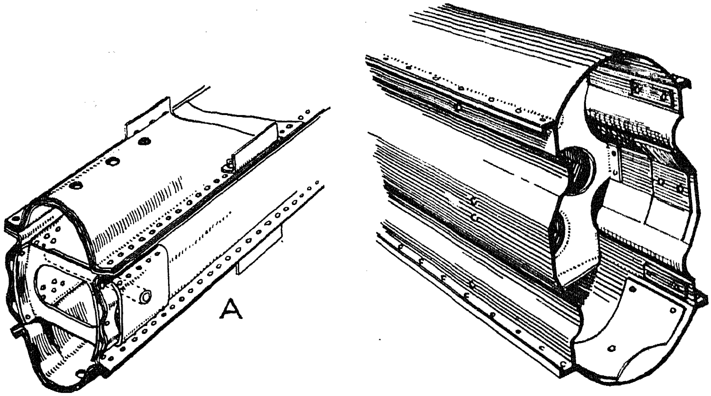

Fig. 8. Duralumin Spars

A, Short. *B*, Handley-Page

(By courtesy of "Flight")

This type of wing may be full or semi-cantilever. It may house the power units and provide support for the undercarriage. In designing such a wing, the thrust and torque of the engines in flight, and the loads from the undercarriage in landing would, of course, be considered.

There is, however, one characteristic common to most of these, and it is that such planes are extremely difficult, if not impossible, to stress mathematically. They are designed on a basis of mechanical testing.

Conventional Biplane Structures

SPARS. The early designs of spars soon showed the need for investigations into the instability of thin materials, a subject which had received little attention from the structural engineer. It was found that spars designed to conventional beam sections failed in buckling long before the maximum direct stress had been reached. With the aid of corrugations, however, the secondary failure could be held back until the stress developed more nearly approached the direct failing strength of the material. The ratio of efficiency becomes $\frac{\text{stress developed}}{\text{maximum stress}}$.

A high value for efficiency may be obtained, but other considerations arise. The spar is not a self-contained member, but must have ribs, drag struts, external bracings, and fuselage attachments. The expense and weight of these fittings must not exceed and ought not to approach the saving on an efficient spar. Again, the efficiency figure of the spar should take account of the cost of its manufacture. It is impossible to say at what point the compromise must be made, but experience and economic pressure are helping the decision. In civilian aircraft the point of compromise is not necessarily the same as in military. A big production will justify the use of an elaborate design more than will a small production.

The general types of metal spars used by British manufacturers are shown in the accompanying illustrations. It will be seen that, although some are of aluminium alloy and others of high tensile steel, the majority fall into two types. In the first type the spar is made in the form of a box from four strips of corrugated metal. In the second there are tubular booms with a single plane or corrugated web.

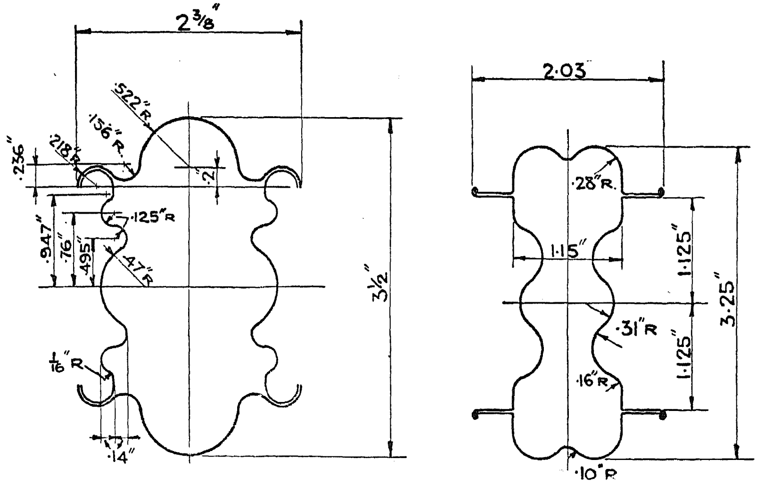

FIG. 9. STEEL SPARS

A, Westland. *B*, Bristol

The Short and Handley-Page spars (Fig. 8) are good examples of the first type. The material is aluminium alloy. The flanges are arcs of circles in section attached to the webs by four outward riveting lips. In the Short spar the web section is also made up from circular arcs, whilst in the Handley-Page short flats are also used. Roughly speaking, these spars are designed on the same theory as the I-beam familiar to structural engineers, in which the flanges cater mainly for the bending stress, the webs for shear, and both for end load. At points of high stress the flanges are doubled up with cover plates, as shown in the Short spar.

The Westland and Bristol sections (Fig. 9) are very similar, but the material is high-tensile steel of a much thinner gauge than that used in the duralumin spars. Whereas the latter may be made of material from 20 s.w.g. up to as much as 14 s.w.g., the steel spars may have webs of 28 s.w.g. On the other hand, the duralumin spar is not expected to develop a stress of more than 20 tons per sq. in., whereas the steel spar gives 65-70 tons per sq. in.[1] Since the steel spar is made of much thinner material, the radii of the corrugations must be less. This point is dealt with more fully later, but the difference should be noticed at this stage. As in the Short and Handley-Page sections, the Westland spar is assembled by riveting along the four lips. The Bristol spar is produced without rivets. The lip on the web is doubled over, the flange lip being drawn into it to form an interlocking joint, which is sufficiently tight to withstand normal shear. At points of heavy loading the frictional resistance may not be sufficient, but the rivets used to secure ribs and fittings usually provide the necessary additional shear strength.

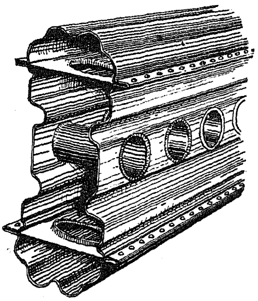

FIG. 10. BOULTON & PAUL STEEL SPAR

(By courtesy of "Flight")

The Boulton and Paul steel spar (Fig. 10) has two additional features in the form of flat plates between web and flange, top and bottom, and tubular distance pieces across the webs. When a spar is subject to bending there is a tendency for the section to distort, the depth becomes

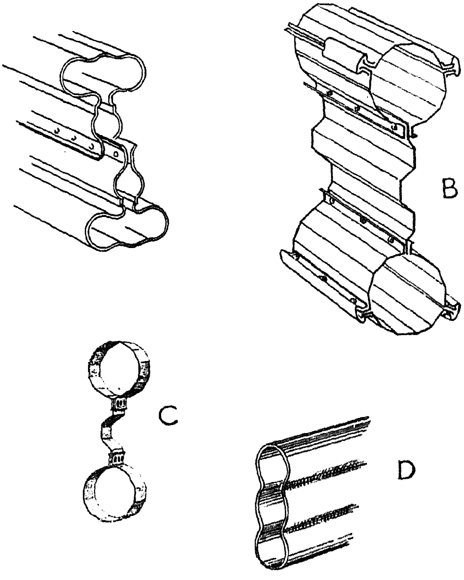

FIG. 11. STEEL SPARS

A, Blackburn *Bluebird* — *B*, Armstrong-Whitworth

C, Hawker steel strip spar — *D*, Solid drawn tube steel spar

(A by courtesy of "The Aeroplane") *(B and D by courtesy of "Flight")*

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[1] See *Handbook of Aeronautics* (3rd Edition) for actual dimensions and strength of typical sections of this kind.

less and the width greater. The moment of inertia is thereby reduced and the resistance of the spar to bending becomes less. The effect of both strips and distance tubes is to prevent this distortion and hold the section up to its work.

On the same general design, but differing slightly in its expression, are the spars shown in Fig. 11. The Blackburn *Bluebird* spar was drawn from only two strips, and had but one line of rivets. The Armstrong-Whitworth section shown in Fig. 11 was, however, made from eleven strips attached in six lines of rivets. Some figures on this spar given by Major F. M. Green [1] will be of interest. They are as follows—

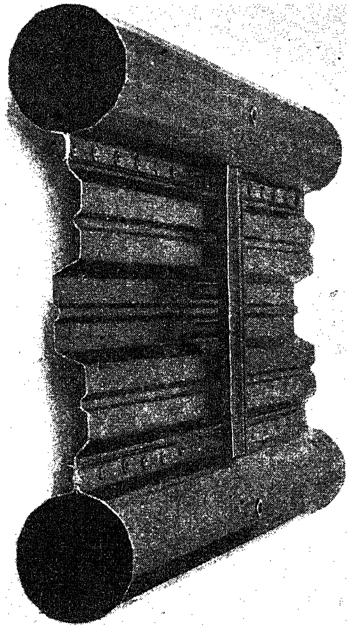

Fig. 12. Armstrong-Whitworth Steel Spar

(*By courtesy of The A.T.S. Co., Ltd.*)

Thickness of flanges	0·02 in.
Thickness of cornices	0·012 in.
Thickness of web	0·01 in.
Thickness of jointing strip	0·008 in.
Outside fibre stress	75 tons-sq. in.
Moment of resistance	30·4 tons-in.
Weight per foot	0·854 lb.

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[1] Fifth International Congress on Aerial Navigation at The Hague, 1930, "The Construction of Aircraft in Steel," by Major F. M. Green, O.B.E., M.Inst.C.E., F.R.Ae.S.

The overall depth is 5·5 in., and the flanges are tangential to circles 1⅜ in. diameter.

The material is a nickel chrome steel strip, heat treated and tempered to a 0·1 per cent proof stress of 65 tons/sq. in.

Major Green states: "The spar . . . has a web 2·7 in. deep and 0·01 in. thick. If this were simply a flat strip, it would be good for an end compression stress of about 1·1 tons per square inch and for a shear stress of about the same value. The corrugations formed in it increase the strength so greatly that it develops a resistance of about 64 tons per square inch in compression and of about 36 tons per square inch in shear before failing. Of course, the corrugations use a little metal, but even allowing for this, by making the flat web 0·012 in. thick, which would make it heavier than the corrugated web, it would still develop only 1·5 tons per square inch and have less than one-twentieth the strength of the corrugated web."

Similar spars have been made up to 10·6 in. deep with 2 in. diameter flanges. These have a moment of resistance of 87·5 tons-in., an outside fibre stress of 70 tons/sq. in., and a weight per foot of 1·48 lb.

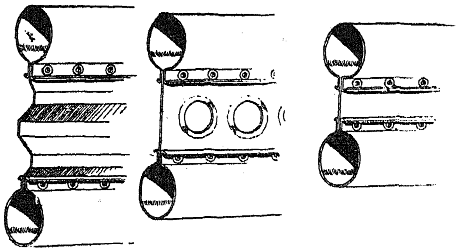

FIG. 13. BOULTON & PAUL STEEL SPARS

(*By courtesy of "The Aeroplane"*)

This kind of spar was later simplified by Armstrong-Whitworth so that it could be made from only three strips. The booms were rolled from a single strip and the top and bottom riveting lips dispensed with. The spar shown in Fig. 12 is 8 in. deep and the booms are of such diameter that they telescope over a 1½ in. tube. With booms ·012 in. thick and a web ·010 in. thick the spar weighs ·7 lb. per foot. It has a moment of resistance of 20 tons.-in. and a failing stress of 60 tons per square inch. When the booms are ·030 in. thick and the web ·015 in. thick, the weight is 1·7 lb. per foot. The spar then has a moment of resistance of 80 tons.-in. and a failing stress of 80 tons per sq. in.

For smaller machines, Boulton and Paul used a three-piece spar (Fig. 13) instead of the six-piece spar discussed above. In the smallest size a flat plate web was found adequate, but when deeper sections were needed it was necessary to stabilize the web. Flanged holes provided stiffness for the intermediate size, whilst the largest required corrugations. The similarity between these and the Armstrong-Whitworth section (Fig. 12) and the Hawker (Fig. 11, *C*) should be noticed. The spar used in the Avro Tutor (Fig. 47) is of the same kind, but the booms are elliptical in section rather than circular.

The Fairey Spar (Fig. 14) is similar in conception. Instead of a circular boom, however, a "double lobe" section is used top and bottom.

This is rolled from flat in one operation, the final shape being obtained by passing the material through a die. High-tensile steel of ·015 in. to ·020 in. is used for the booms, whilst the flat plate web may be anything up to ·030 in. thick. Local stiffness is attained by inserting liner pieces in the booms, and doubling up the web by extra side plates. Additional stability is given by small vertical gusset plates riveted to the web at intervals of about 10 in. These are flanged over top and bottom to bear against the "lobes" of the booms.

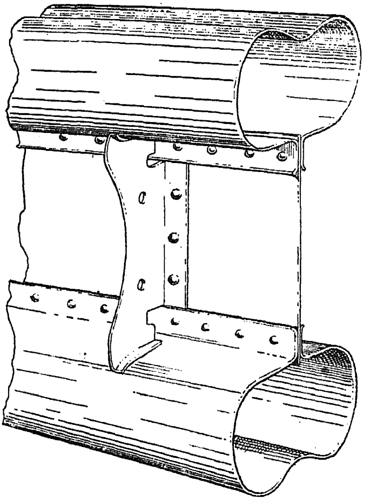

FIG. 14. FAIREY STEEL SPAR
(By courtesy of the Fairey Aviation Co., Ltd.)

Boulton and Paul developed a two-piece spar (Fig. 15) for light planes. It had no rivets, and the two strips were joined along the centre line, top and bottom, by interlocking joints. The shear is, of course, a minimum here, and the roll provides additional stiffness against failure in compression. The smallest spar of this kind has A = 2·2 in. B = ·875 in., and the outside fibre stress at failure is 65 tons per square inch, the material being S88 or D.T.D. 46A. To give extra stability short pieces of tube are put into the centre lobe at intervals and secured by tubular rivets passing right through from side to side.

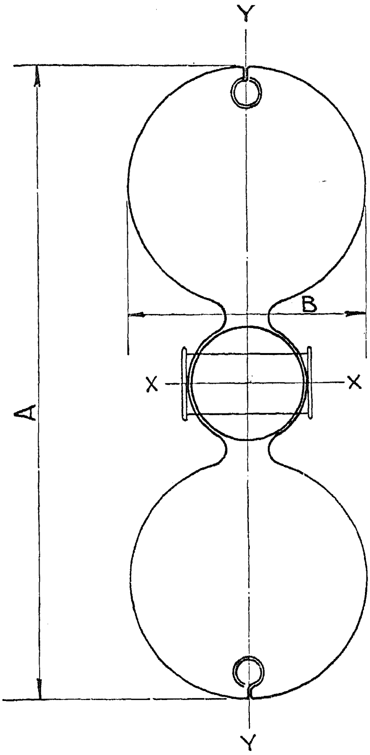

FIG. 15. BOULTON & PAUL STEEL SPAR

The simplest spar of all is the solid drawn tube illustrated in Fig. 11, *D*. This is made by the tube manufacturers and supplied to the aircraft industry in the finished condition. It is cheap, but since the web is the same thickness as the flange there is clearly some loss in efficiency. Doubling at points of high stress may be achieved by inserting lengths of round tube into the outer booms, securing them with tubular rivets. This section has been used by Fairey, Gloster, and Hawker.

Another type of spar to which reference was made earlier was that in which strength-weight efficiency was thought to be of less importance than a design which allowed the use of a simple type of fitting and an economical production in small quantities. As was stated before, a big production will justify a more elaborate design, since capital may then be laid out in jigs and fixtures. Two examples of a simplified design are given in Figs. 16 and 17.

The construction of both these spars is extremely easy, and most of the operations can be performed by unskilled labour. The channels which formed the flanges of the *Viastra* spar were extruded and supplied by the duralumin manufacturers finished to shape. They required only simple riveting to attach the web and flange doubling strips. The "wandering web" which was attached alternately to each side of the spar performed the work of both web and diaphragms.

The Supermarine *Scapa* spar consists of ribbed channel booms with a single corrugated web. This spar is extremely simple to construct as all the riveting is accessible from both sides. The section is not, however, stable in itself, a feature common to most of single web or "dumb-bell" form. It is stabilized by pressed diaphragms and the angles which serve to carry the ribs.

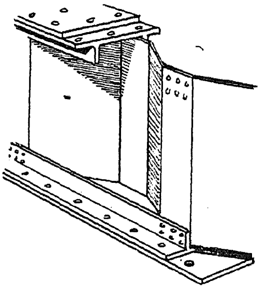

FIG. 16. VICKERS "VIASTRA" SPAR
(*By courtesy of "The Aeroplane"*)

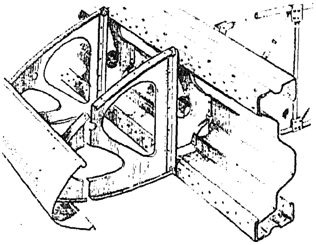

FIG. 17. SUPERMARINE "SCAPA" SPAR
(*By courtesy of "Flight"*)

Spars of this kind give weight as the price for constructional simplicity and though they may develop a stress of perhaps 18 tons per square inch, they achieve stability by bulk of metal rather than by corrugations, and so would not be possible in steel. Duralumin is the material used. In a magnesium alloy still greater bulk might be given for the same weight, thus improving the moment of inertia and consequently the stability.

The problem of the instability of thin flat and curved plates has been investigated mathematically,[1] but the results do not justify their use in practical spar design. The question is one of extreme complexity, and any general formula for its solution must take into account the relation of each curve and flat in the cross-section of a spar to its neighbour. A number of empirical rules have been built up out of the experience of actual spar testing, and though mathematicians might eventually provide a solution, very satisfactory results have been obtained in practice.

The maximum radius of a corrugation or width of a flat depends on the thickness of the material, its maximum stress, and, in a corrugation, the angle of the arc. Flats should be used sparingly, and in duralumin should not be wider than ten times the thickness. In high-tensile steel this figure may be increased to fifteen times the thickness. The corresponding ratios of radius to thickness in corrugations should not exceed thirty for aluminium alloy and forty-five for steel. These rules need applying with discretion and are subject to various limitations. Wide flats and large radii should always be separated by small crinkles, and the angles between them should not approach 180 degrees. A spar web which was designed as shown in Fig. 18 failed at a low stress in vertical bending, but was greatly improved when altered to the shape given in Fig. 19.

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[1] *Flight* (Eng. Supplement), 29th March, 1928.

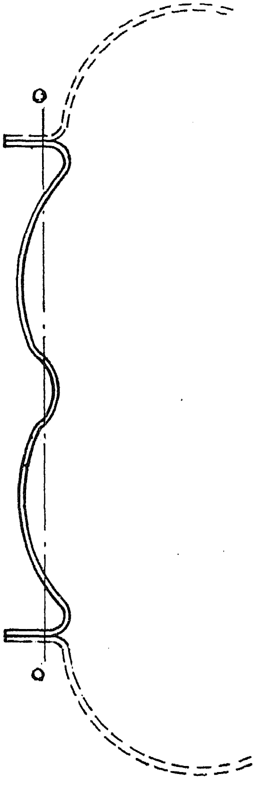

FIG. 18

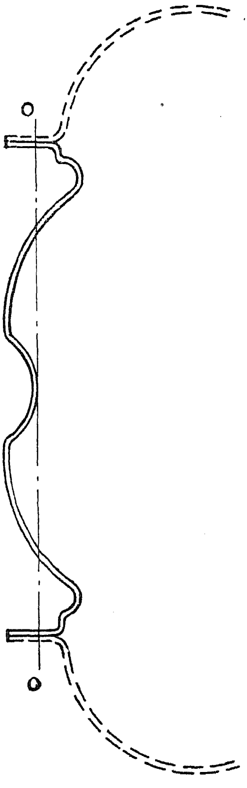

FIG. 19

It will be noticed that the material is disposed farther away from a mean line OO in Fig. 19 than in Fig. 18. The moment of inertia of the web about this axis was obviously greater in the second example, and, though the axis is not one which enters into a calculation of the I of the spar as a whole, yet it evidently plays a part in its stability.

There are flats other than those designed which must be watched for. When drawn, a section such as Fig. 20 tends to develop a flat along the line yy at the point where the two radii are tangential. A method of preventing this is to make the radii not tangential, as in Fig. 21. The break in line should, however, not be sharp, and a small radius of not less than the thickness of the material put in.

A further point where instability has been found to occur is at the riveted flange of thin steel strip spars. Buckling between the rivets is extremely likely to happen when this is designed as in Fig. 22, *a*, but methods of overcoming it are shown in *b*, *c*, and *d*.

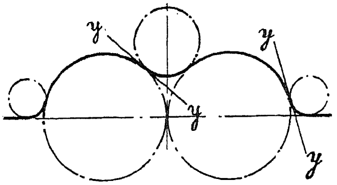

FIG. 20

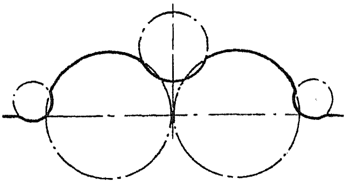

FIG. 21

A very practical consideration enters into the design at this point. It was found impossible to hold up the rivets for hammering over in flange shown in Fig. 23—the web crinkle was in the way of the riveting dolly, but when the flange was modified to Fig. 24 the difficulty was removed.

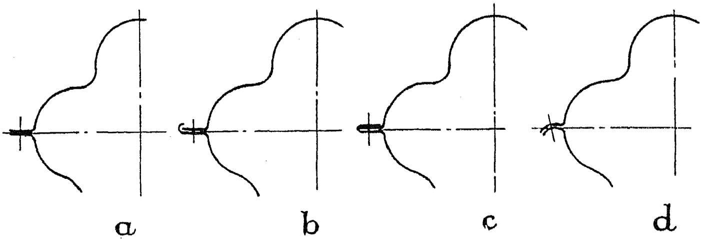

FIG. 22

The rivet size and spacing depends on the thickness of material in the flange and web.[1] A certain latitude is allowable. Thus where a 16 s.w.g. flange is doubled up over a short length with a 14 s.w.g. cover plate, it is a convenience to continue the same size and spacing of rivets through the length of the cover plate as in the ordinary spar.

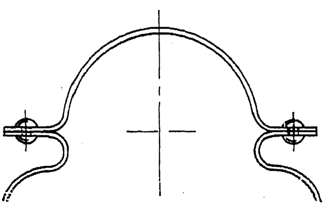

FIG. 23

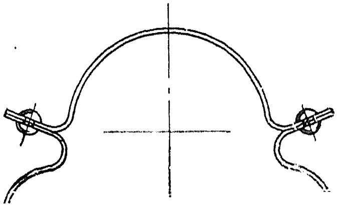

FIG. 24

Whilst not altering the pitch, intermediate rivets may be inserted if necessary.

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[1] See Chapter IX, for rivet diameters appropriate to various thicknesses.

The width of flange is governed by the rivet size. There should always be a width of flange outside the rivet centre line at least equal to twice the rivet diameter. In steel spars where the edge is doubled back (Fig. 22, *c*) this dimension refers to the shorter and inner of the two flanges. A narrow width of flat must also be allowed on the inner side of the rivet to prevent the material being damaged by the riveting snap. The deciding case is at the point in the spar where the flange is covered by a doubling. If the same cross centres of rivets are then maintained throughout the whole length, the jigging and tooling will be much simplified (see Fig. 25).

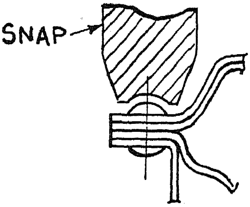

FIG. 25

An unusual form of wing spar was used in the Curtiss Kingbird, and nothing of the kind has appeared in England. Although this machine was a monoplane, the wing structure was fabric-covered and, in general lay-out, of the conventional type of constant chord and thickness. The spar (Fig. 26) was made up with welding. The top and bottom flanges were oval tubes and the warren girder bracing of round tube. Small lugs were spot-welded above and below to take the ribs. The spar root was heavily stiffened with welded gussets. It would be of value to have comparative weights, since a spar of this kind might be suspected of heaviness. There is, however, no doubt that, for small numbers, it is extremely cheap to produce.

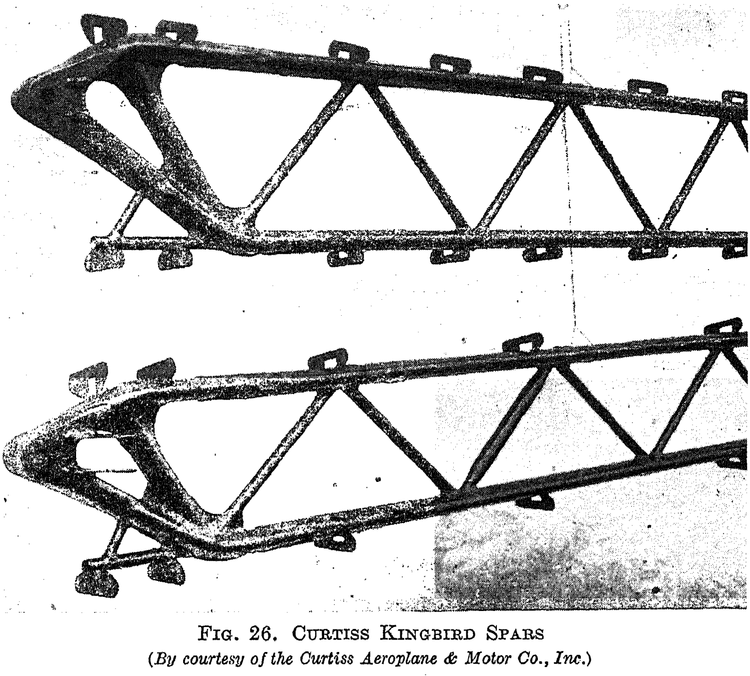

FIG. 26. CURTISS KINGBIRD SPARS

(*By courtesy of the Curtiss Aeroplane & Motor Co., Inc.*)

Another monoplane structure may be included in this section since it is of the fabric-covered type with external lift and internal drag bracings. It is the Russian Stal II designed by Poutiloff. The spars (Fig. 26A) are open girders having corrugated flanges and built-up channel shear bracings. The material is stainless steel strip, but the novelty of the construction lies in the use of electric spot welding (see page 374) instead of riveting for making all the connections. Similar methods are used in the fuselage (page 216).

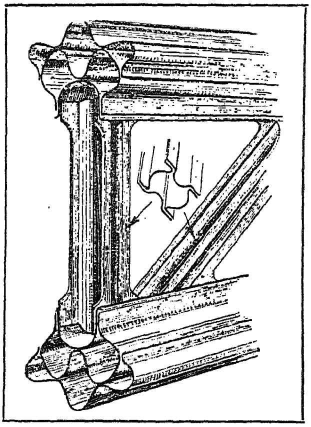

FIG. 26A. STAL II SPAR
(*By courtesy of "Flight"*)

SPAR STRESSING. The methods of obtaining the constants (Moments of Inertia and Section Modulus) of a wooden spar are usually simple. They are given in any textbook of engineering or mechanics. Having been found, their application is straightforward since secondary

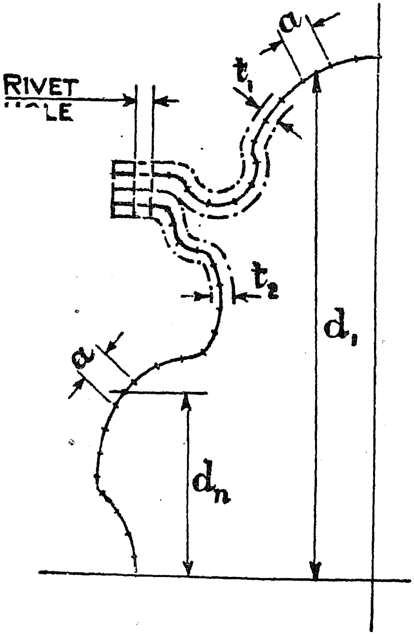

FIG. 27

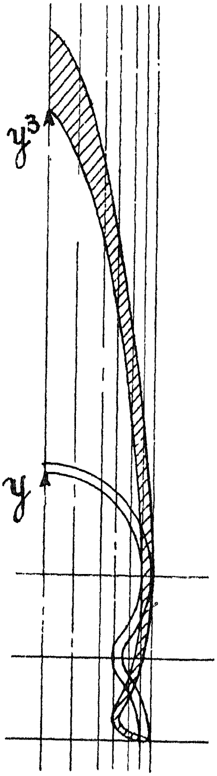

FIG. 28

failure is unusual and the full strength of the material may be developed. In a corrugated metal spar the methods of calculating the constants are simple when understood, but their application is more difficult. Unless a considerable amount of test data has been accumulated, it is almost impossible to say what stress will be developed in any type of spar. Not only does secondary failure usually cause collapse before the full direct stress is developed, but, owing to the greater elasticity of the high-tensile materials, deflection is of a comparatively large order. The question is dealt with fully in the "Design Requirements for Aeroplanes for the Royal Air Force," Air Publication 970.

The Air Ministry ruling on developable stress is that a test must always be carried out, unless considerable knowledge exists regarding the strength of the spar form in question.

The simplest method of estimating the moment of inertia of a metal strip spar is that given in the above publication, Chapter VI, para. 2.

A quarter section of the spar is drawn out on a large scale. It is sufficient to indicate the centre lines of the thickness of material, as in Fig. 27. The section is then divided up into small elements of length *a* inches (*a* may be 0·10 in. for small spars and 0·25 in. for large spars). Since rivet holes on the tension side of the spar reduce the strength in proportion to their diameter, this small section is removed from the calculation.

1	2	3	4	5
Element No.	Area of Element	Distance from Neutral Axis	Col. 3 Squared	Col. 4 × Col. 2
Flange—				
1	$t_1 \times a$	d_1	d_1^2	$(t_1 \times a) \times d_1^2$
2	,,	d_2	d_2^2	$(t_1 \times a) \times d_2^2$
3	,,	d_3	d_3^3	
4	,,	d_4	d_4^2	etc.
to		etc.	etc.	
n_1				
Web—				
1	$t_2 \times a$			
2				
3	,,			
4	,,			
to				
n_2				
	Add up to X			Add up to Y

Area of section : $4 \times X$
Moment of inertia : $4 \times Y$

The Moment of Inertia may also be found graphically with the use of a planimeter. Given accurate drawing, this method is both quick and simple. A quarter section of the spar is drawn on squared paper, the exact thickness of the material being indicated. The vertical ordinates to both inside and outside of the thickness are cubed and set up above the base. Curves are drawn through the points obtained. The area between these curves (shown shaded in Fig. 28) is read off on a planimeter, and the result which is obtained we may call BD³. The Moment of Inertia of the whole section is $\frac{4BD^3}{3}$.

The diagram illustrates very clearly which part of the spar is most effective in resisting bending.

A purely mathematical method of calculating the constants was given in the *Handbook of Strength Calculations*, Appendix XVI. This has been developed by Mr. H. J. Pollard into a quicker tabulated form.[1]

The degree of accuracy which is required in these estimations is not extremely high.[2]

SPAR TESTS. The method of carrying out spar tests is laid down by the Air Ministry. Since more test work of this description has been carried out by the Royal Aircraft Establishment at Farnborough than anywhere else in this country the methods employed there will be described first.[3]

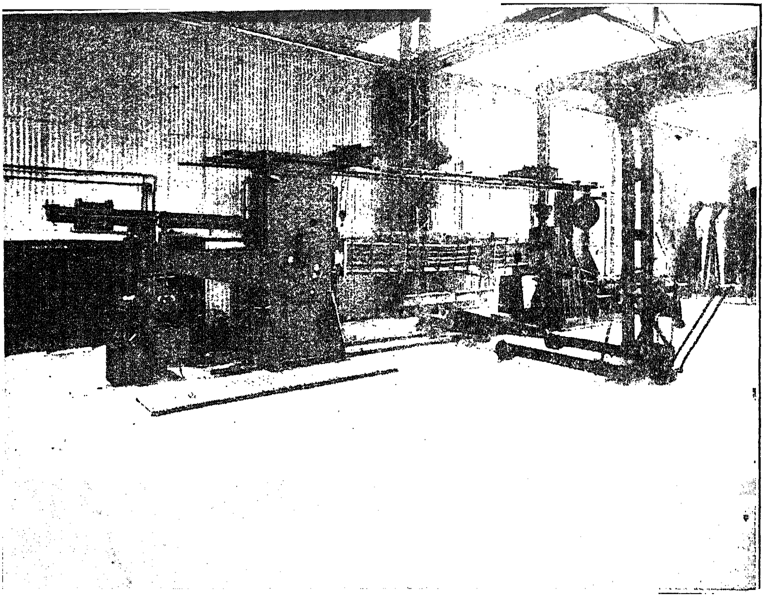

FIG. 29. SPAR TESTING MACHINE
(*Crown Copyright*)

In a biplane structure the condition in one of the inner bays is more complex than that occurring in the overhang, owing to the end load from the bracing. Two cases are considered and a test made to represent each. The first is that of maximum end load combined with the corresponding bending moment, and the second that of maximum bending moment combined with the corresponding end load.

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[1] *Flight* (Eng. Supplement), 25th April, 1929, p. 338*a*.

[2] In a large production, finer limits in spar size may be achieved than in a small production. The larger limits allowable in experimental work together with ± limits on the thickness of material should be accounted for. If oversizes of all these dimensions occur together, a very false figure of maximum safe stress may be obtained. For economic reasons, the designer should not demand extreme accuracy in the works, unless production is on a large scale. One might suggest that the alteration of drawings and figures is cheaper than the alteration of dies and rolls. This suggestion is not made to give the works unlimited licence, but merely to acknowledge the difficulty of shaping a die to produce a given section, making allowance for "spring back" in the drawn metal.

[3] *Journal R.Ae.S.*, July, 1931, "Mechanical Testing in Aircraft Construction," I. J. Gerard.

Journal R.Ae.S., September, 1932, "Mechanical Tests of Aircraft Structural Components," I. J. Gerard.

A length of spar is taken which, with end fittings, is of length equal to the distance between points of contraflexure as found from the bending moment diagram. The end fittings are made to carry pins running in the direction of, and on, the minor axis of the section. The spar is set up with the major axis vertical and supports are rigged to represent the stabilizing effect of ribs and drag members. The end load is applied directly by an horizontal compression testing machine. The transverse load is applied at two points, one-quarter of the spar length from each end. The ratio between end load and transverse load is kept constant through successive increments. At each stage the deflection at the midlength is measured.

The stress developed in the outer fibre at failure is taken as the sum of—

1. The end compressive stress, P/A
2. The direct bending stress, M/Z
3. The bending stress due to end load, Py/Z

where P = End load.
A = Cross-sectional area.
M = Bending moment due to transverse load.
Z = Section modulus.
y = Deflection at mid-length.

The machine used is shown in Fig. 29. This is capable of taking specimens up to 100 ft. long and applying an end load up to 100 tons. The transverse load is applied through the crane in front of the test. The pull is taken through a spring balance to a lever system, whence it is transmitted to a steel girder hung under the spar. The links which apply the load to the spar are attached to the ends of the girder.

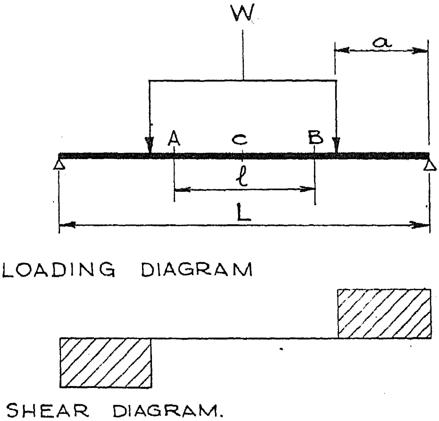

FIG. 30

It will be seen that this method of testing applies no shear to the spar between the loading points. Some metal spars, however, when tested under more realistic conditions, have shown a deflection in excess of that which could be attributed to bending. It has been demonstrated that this excess is due to shear. A further test has therefore been devised in which shear is applied to the spar and the difference in deflection between the tests is that caused by the shear.[1] It is thus possible to establish the "Shear Constant r" such that

$$\frac{dy_s}{dx} = -rS \qquad \text{where } S \text{ is the shear, } y_s \text{ is the shear deflection.}$$

The spar is first tested as for the first method but without the end load, and the deflection, y_b, at C measured over a length AB (Fig. 30), for increments in value of W.

The ratio W/y_b may be found by plotting the results.

$$\text{Then } EI = \frac{aL^2}{16} \cdot \frac{W}{y_b}$$

Having established EI in the above case, that is, without shear, the second test should be made.

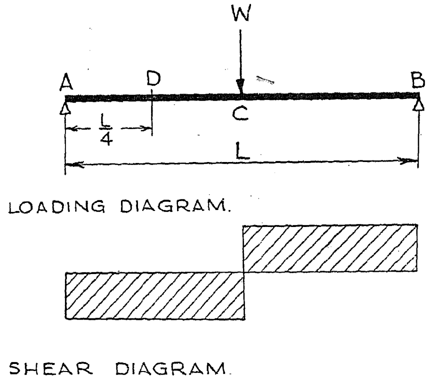

FIG. 31

W is now applied as a point load at the mid length. Shear forces therefore act.

The deflection, y, of C (Fig. 31) is measured over the length AB for increments of W and the results plotted. The ratio y/W is thus established.

Then y_s (shear deflection)

$$= y - y_b$$

$$= \left(\frac{y}{W} - \frac{L^3}{48EI}\right) W$$

and r (shear constant)

$$= \frac{4}{L}\left(\frac{y}{W} - \frac{L^3}{48EI}\right)$$

To check the result, take readings at another point, D, situated at $L/4$ from A. If the deflection at D is denoted by y_d, then

$$r \qquad \cdot \frac{y_d}{W} \cdot \cdot \frac{11\,L^2}{96EI}$$

The value of EI used in this is, of course, the one found in the previous test. Any errors in the estimation of I are thus eliminated together with variations in both E and I. The result therefore represents the true spar.

The shear constant, r, thus found is used in the extended form of the Three Moments Theorem, which includes Shear Deflection.

Major Wylie has suggested a modification of the above method[2] whereby the crippling stress of the spar, EI, and the value of r may all be established from one test piece.

The length of the test piece might be taken at sixteen times the spar depth. The ends are reinforced to make them capable of withstanding end loads without local failure. The load is applied at fittings spaced at the same pitch as the ribs, but in order that the full shear load may be reached in such a short specimen each load would have to be bigger than that normally applied by the ribs.

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[1] "Design Requirements for Aeroplanes for the Royal Air Force," A.P. 970.

[2] *Journal R.Ae.S.*, September, 1932, p. 691.

The transverse load is in the first place balanced by an offset end thrust such that the bending moment at the centre is equal to that at the ends. The shear deflection is then zero and *EI* may easily be calculated.

The transverse load is then made such that the bending moment deflection, under the influence of the offset end load, is zero. The actual deflection occurring is thus entirely due to shear. The shear constant, *r*, is directly calculable. These cases are carried up to a stress of about 80 per cent of the maximum safe stress.

The third case is taken in which sufficient transverse load is applied to show that the shear strength is adequate. The bending stress is kept down to safety by applying appropriate end moments.

In the final test, the end thrust is applied on the neutral axis in increments with the transverse load until failure occurs. The value of *r* is used to calculate *EI* up to the failing stress.

Major Wylie emphasized the importance of reproducing realistically the actual conditions of the structure by quoting a test on a long length of corrugated strip spar in which the transverse load was applied in the conventional way through one or two improvised fittings. The shear deflection was found to be 15 per cent of that due to bending. In the actual machine, however, the rib attachments were such that the application of load tended to deepen the spar and thus increase the value of *EI*, whereas in the conventional test the spar tends to spread sideways and the value of *EI* to become less. When the true conditions were reproduced on test, the shear deflection was found to be a negative quantity.

If the test is being carried out to show that a particular spar is strong enough, rather than to establish the constants of the section, the method illustrated in Fig. 32 may be used.

In this test, made by Messrs. Short Bros. Ltd., a whole spar, including end fittings was rigged up. The load was applied at close intervals representing the rib spacing. Very small weights were required with the ingenious but simple system of levers. The overhang, of course, has no end load, but the compression on the inner bay is applied automatically by the inclined tie.

The final test to which this leads is one in which the whole wing structure is rigged upside down and loaded with shot bags. In this way the transference of load from one spar to the other through the ribs and drag struts is taken into account and the torsional deflection of the plane measured. The strength of the detail fittings and their attachments is also proved.

There are, however, two factors which can only be given in actual flight tests. One is the time factor which is introduced when the load is suddenly applied and may as suddenly be released. Vibration and consequent fatigue may have effect which can never be satisfactorily reproduced in the laboratory.

Nevertheless the special methods of mechanical testing which have been built up by the Royal Aircraft Establishment and the private firms still form the essential link between theory and practice.

FLANGE DOUBLINGS. Since the loading in a spar varies along its length, it is obvious that the theoretically efficient spar is one in which

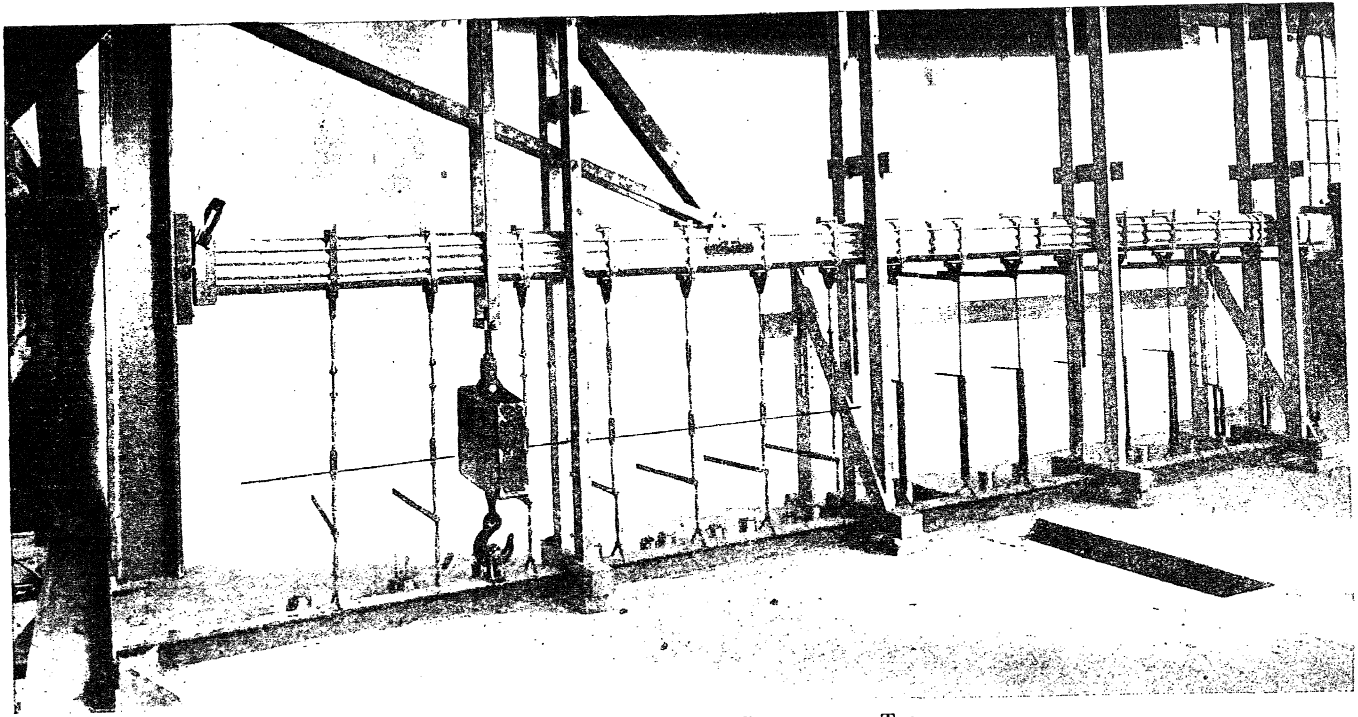

FIG. 32. SHORT DURALUMIN SPAR UNDER TEST

(By courtesy of Messrs. Short Bros. (Rochester and Bedford), Ltd.)

the material is so disposed that an equal stress is developed at all points. Such an ideal cannot be efficiently attained. But it does not follow that the whole length of spar should be designed for the point of heaviest loading. A compromise must be made. The spar proper is made suitable for a light loading, and doubling plates, as already illustrated in the Short spar (Fig. 8), are added to the flanges to increase the moment of resistance over the lengths of heavier loading.

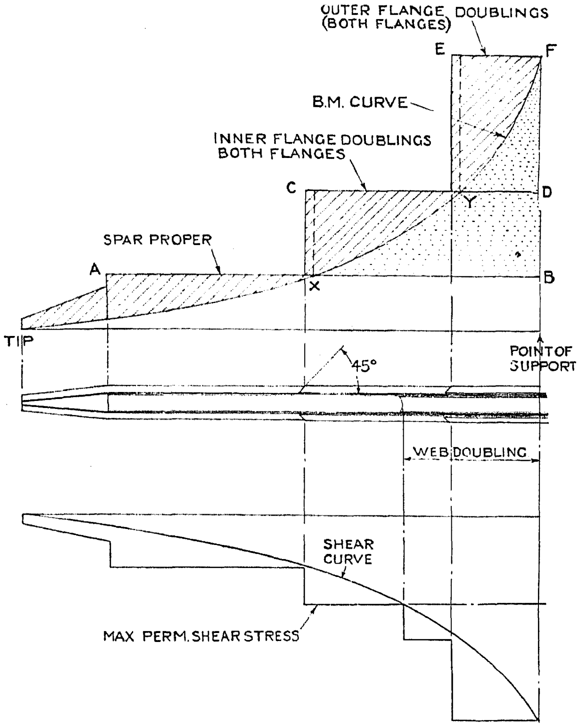
OUTER FLANGE DOUBLINGS (BOTH FLANGES)
E
F
B.M. CURVE
INNER FLANGE DOUBLINGS BOTH FLANGES
C
D
Y
SPAR PROPER
A
X
B
TIP
POINT OF SUPPORT
45°
WEB DOUBLING
SHEAR CURVE
MAX PERM. SHEAR STRESS

FIG. 33

The simplest example is that of a cantilever spar or overhung end. (See Fig. 33.)

The moment of resistance of the spar proper is calculated and superimposed as an horizontal line *AB* on the bending moment curve. It will be seen how much this falls short of taking the peak load (indicated in Fig. 33 by the dotted portion of the curve). Suitable thicknesses of doubling plates are decided on. It may be necessary to use two or more over the worst length. The moments of resistance of the spar with first one and then both of the doublings are estimated [1] and added to the diagram as horizontal lines *CD* and *EF*. The doublings may end at the points *X* and *Y*, but it is well to carry them on for an inch or so. The position of the doubling may then be given a wider tolerance to cover variations in the positions of rivets along the riveting lips. Unless the jigging is elaborate, it is difficult to guarantee that the rivet spacing and positions will be exactly the same in a series of spars. Violent changes in section must be avoided in any engineering structure. The doubling, therefore, should be chamfered off at some convenient angle not greater than, say, 45 degrees beyond the length already decided.

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[1] If the characteristics of the spar are not very familiar, these calculations should be backed up by tests since the maximum developable stress of the material is not necessarily the same as in the spar proper.

A lighter spar could be made by stepping the material up a smaller amount at each of more frequent intervals. Doubling plates, however, are a trouble in the works, and it is better, therefore, to be satisfied with slightly less efficiency in this respect. The hatched portion of the diagram indicates the amount sacrificed on this score. It is sometimes an advantage to put a doubling plate on one flange only—the compression side—thus raising the neutral axis and giving a more economical method of increasing the modulus.

Having thus catered for the bending moment, the direct shear stress must be considered. It will probably be found that there is already sufficient material to take it. If not, or if the deflection is excessive, then the usual method is to add web doublings and reduce the pitch of rivets in the lip. The treatment is exactly similar to that for the flange doublings, and the ends must be cut back to avoid a sudden change of section (see Fig. 33). It is usual also to use a web doubling to take the strut or other fittings whereby this shear stress is transmitted to the spar. The point will be considered later under fitting and joint design.

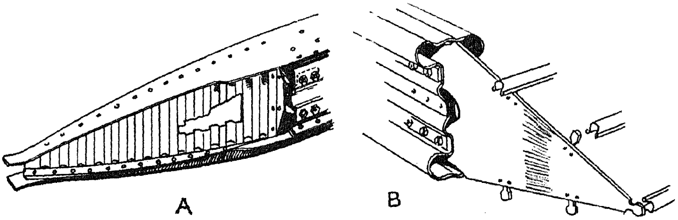


FIG. 34. TAPERING SPARS
A, Handley-Page. *B*, Blackburn
(*A by courtesy of "Flight"*) (*B by courtesy of "The Aeroplane"*)

The horizontal shear is taken from flanges to webs through the rivets. Though the spacing required may be calculated, it will probably be found that the riveting table given in Chap. IX will cover the case. Any weakness will at once be shown up in the test and is easily corrected.

Splices. It is frequently necessary to make a break in the flanges or webs due to a change of thickness or restriction in the length of material. If it is possible, this should be arranged at a point of contraflexure where there is only end load to transmit. Such a break must be covered with a doubling. The obvious method of taking the compression is through a butt. Since this implies a perfectly fitted surface in each of the ends it is likely to be expensive. A definite gap should be allowed between the two ends and the entire load taken through the doubling. The material must be of sufficient area to take the compressive stress and the rivets of sufficient number to take the load in shear and bearing on each side of the joint.[1]

---

[1] A table of rivet shear and bearing strengths will be found in Chapter IX.

Reference has already been made on p. 35 to the use of short lengths of tube as doublings in such spars as the Hawker, illustrated in Fig. 11. They may be similarly used in splices. The principle is the same in each case, but the most suitable method of attachment is perhaps by tubular or "pop" rivets.

SPAR TIPS. The tapering of spars throughout their length will be dealt with in special forms of constructions later. In the conventional types of biplane structures with parallel spars it is usual to taper the wing tip. The spar must consequently be tapered over a short length at the end. As there is no end load here and the bending moment fades out to nothing, a considerable saving of weight may be achieved in the tip.

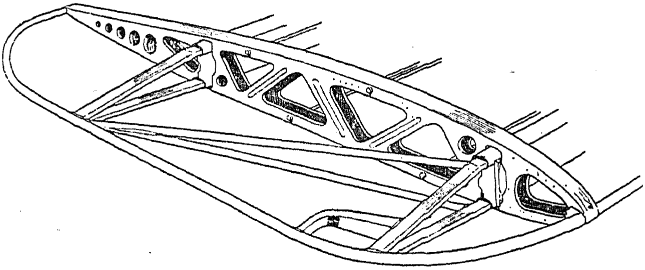


FIG. 35. AVRO TUTOR WING TIP

(By courtesy of "The Aeroplane")

In spars such as the Armstrong-Whitworth, Boulton & Paul, and Hawker steel strip spars in Figs. 11, 12, and 13, and the Vickers *Viastra* spar (Fig. 16), no special difficulties present themselves. Fig. 34 illustrates methods used by different manufacturers of corrugated spars. They are both straightforward. In addition to the small bending and shear loads, there are likely to be handling stresses which cannot be dealt with in calculations.

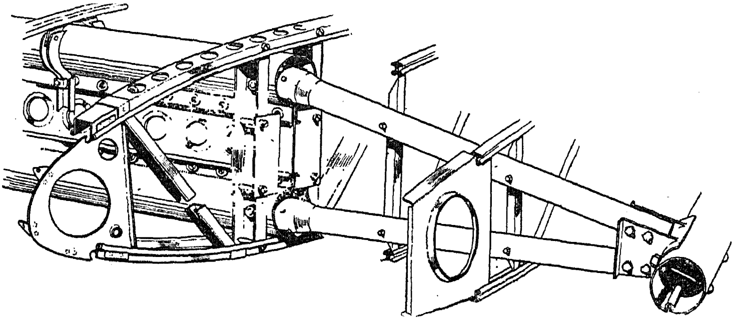


FIG. 36. BOULTON & PAUL SPAR TIP

(By courtesy of "The Aeroplane")

Where spars of "dumb-bell" section are used the taper may be made as shown in Fig. 35. In the Avro Tutor the whole wing tip is made up in one piece, by welding. Tubes are inserted in the ends of the top and bottom booms of the spar and brought together at the tip tube. The fitting behind the front spar which bends to the tip tube marks the position of a hand hole and carries the fabric edge. The whole unit is easily detachable for repair or replacement.

The Boulton and Paul method is similar, but welding is not used. The joints are bolted, and, this being for a larger machine than the "Tutor," there are two ribs between the last full contour and the tip.

DIAPHRAGMS AND DISTANCE PIECES. A method of attaining stability in a spar is to fit diaphragms or distance pieces at frequent intervals. Since they carry no direct stress and merely react against secondary loads, they make little appeal to the theorist who desires the perfect structure in which every part is equally stressed and under primary loading. Nor are they popular in the works, as their presence implies a confusing multiplicity of parts.

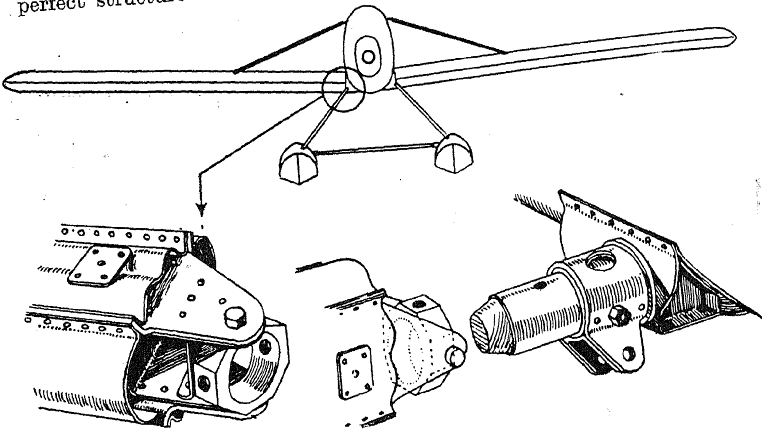


FIG. 37. SHORT "MUSSEL" SPAR JOINT

(*By courtesy of "Flight"*)

There are cases, however, in which they cannot be avoided, particularly in thin steel strip spars, or when, owing to special circumstances, they may provide a solution to a difficult problem, but it is not easy to quote an example of such a solution. With care in detail design they might be made to serve a double purpose, in acting as stiffeners and in holding parts together during manufacture, thus reducing the number of jigs. At joints and fittings where it is necessary to have great rigidity in the spar and to transmit the load to all its parts, diaphragms and distance pieces are fully justified. But this is a different case, and will be dealt with under the design of such fittings.

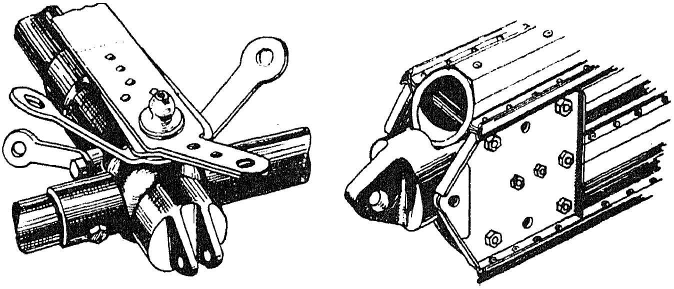
SPAR JOINTS. It is much easier to design a spar which is good in itself than to design one which is not only efficient as a beam, but which lends itself to simple types of joint fitting, bracing attachment and rib fixing. Such points should be considered at a very early stage and typical details drawn out and tested.

Very considerable ingenuity is required in joint design. The fittings must be efficient as stressed parts—that is, they must carry their loads with the minimum of weight and maximum of stiffness. They must be cheap in production and simple to replace, though hard-wearing. A multiplicity of similar pieces made by an easy repetition process may appeal, but should be weighed against the cost of putting those parts together when more complicated ones, fewer in number, might be used.

SPAR JOINTS TO FUSELAGE. A few joints from existing machines will be taken and analysed in detail. A very simple example is that of the Short *Mussel*, a low-wing float monoplane. Fig. 37 indicates the position and form of the joint.

The loads are self-evident. There is no bending moment in the spar at the pin, though the fuselage stub is in bending. Tensile and compressive end loads are imposed by the strut to the top of the fuselage, and there is shear in the vertical direction. Drag imposes tension and shear horizontally.

The gimbal mounting is used to facilitate erection and to ensure that there is no fixing moment. The gimbal itself is machined from solid steel, but might be made in duralumin if the loads are small. The side plates which carry it are very well attached to the spar. Being secured in the riveting flanges, they distribute the load evenly. To prevent secondary failure, two channels are put in across the line of the spar, acting as distance pieces.



Fuselage side Spar side

FIG. 38. ARMSTRONG-WHITWORTH SPAR JOINT

(By courtesy of "Flight")

A more complicated joint is shown in Fig. 38 and is taken from Armstrong-Whitworth practice. The machine is a wire braced biplane, and an extra member, the lift wire, is introduced into the problem. The lug for holding this wire is on the fuselage side of the joint, where it has no offset. The vertical component of its load passes straight up the fuselage strut. Great attention has evidently been paid to attaining stiffness in the spar root. The tubular booms have been doubled up with thick inserts. The direct end load, taken by the machined socket, is transmitted and spread by the thick side plates, which are, moreover, flanged at the edges to strengthen them sideways. Owing to the direction of the main joint pin, the end is partially fixed against the horizontal bending moment imposed by the drag load. Fig. 39 shows this spar end from the opposite side with drag strut and bracing, etc.

When folding wings are fitted, the lift and anti-lift wires are not taken across to the fuselage side of the joint, and the connection must be stiff enough to carry the vertical components in bending across the hinge.

Owing to the initial tension in the wires, which would cause distortion, a jury strut must be put across the gap between top and bottom front spars before folding. This strut is usually a light telescopic member with a quick release at its lower end so that it hinges up out of the way when the machine is in flying trim.

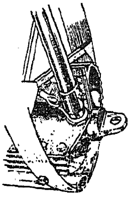


FIG. 39. ARMSTRONG-WHITWORTH SPAR JOINT

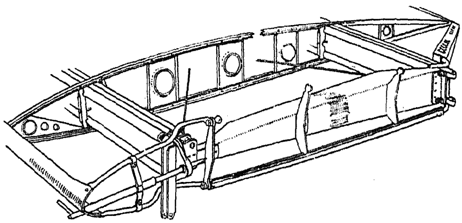


FIG. 40. BLACKBURN "BLUEBIRD" WING ROOT

(*By courtesy of "The Aeroplane"*)

Fig. 40 shows the inner end of the starboard upper main plane of a Blackburn *Bluebird.* The spars are of the kind illustrated in Fig. 11. The vertical hinge bolt will be noticed at the rear spar, and the horizontal draw bolt with its guides at the front spar.

The root end of a spar of the Fairey type is shown in Fig. 41. The top and bottom booms are plugged for a short distance with light alloy blocks cast to shape. The web has an extra stiffening piece let in and light box fittings provide vertical stability. Bearing loads of the two root attachment pins are taken by side plates of nickel steel which are riveted to the spar through the top and bottom booms. The root drag strut and drag bracing are led to a point on the spar centre line where

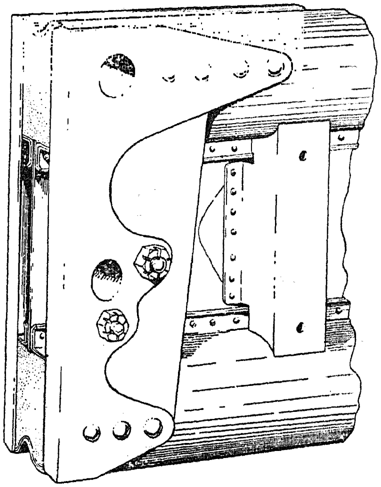


FIG. 41. FAIREY SPAR ROOT

(*By courtesy of the Fairey Aviation Co., Ltd.*)

they pick up on an eyebolt which passes through the assembly of spar web, stabilizing boxes and side plates.

In all the joints discussed the highly stressed fittings themselves have been of steel, whatever the material of the spars. The spar end, to which the joint fitting is mounted, must be adequately strong and stiff to take the load. The Handley-Page spar end (Fig. 42) is a case in point, and is here illustrated without the fitting. A thick duralumin doubling is inserted and riveted to both flanges and webs by sufficient rivets in both shear and bearing to transmit the end load to the spar. The fitting attaching bolts (not shown) pass through the flat sides of this doubling, which is itself doubled up by the small square plates to give adequate bearing for these bolts. That portion of the load which is taken by these small bearing plates is transmitted to the main doubling by the twelve countersunk headed rivets each side. Additional transverse stiffness is attained by the horizontal channel distance pieces.

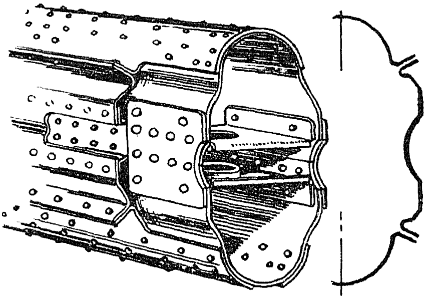


Fig. 42. Handley-Page Spar Root

(By courtesy of "Flight")

STRUT AND BRACING JOINTS. We now come to a consideration of the remaining joints on the wing and their design in relation to the spar. The most complicated case is that in which both external and internal bracings meet at a point. The members may consist, in an externally braced biplane, of lift and anti-lift wires with an interplane strut, and drag and anti-drag wires with a drag strut, as well as an incidence wire. Such an arrangement is shown diagrammatically in Fig. 43. The joint is on a lower front spar, port side. The centre lines of all the members are produced (dotted) to meet at a point on the spar centre line. An actual joint of Boulton & Paul design, embodying these members in the same order, is illustrated in Fig. 44. The lugs for the lift and anti-lift wires are clearly visible, being double, one on each side of the spar, the wire in each case being fastened by a standard fork end to a shackle which bridges the gap between the lugs. The lugs for the drag and anti-drag wires are also seen clearly. These are each single, the wires being attached directly by fork ends. The drag strut (not shown) comes into the vertical channel on the spar side, and the interplane strut into the bridge piece across the top of the spar, its bolt passing through in a fore and aft direction. The incidence wire may be attached either to a lug under the head of this bolt or the bolt may have a machined eye head.

Various other points will be noticed on a close examination of the drawing. The spar web has been stiffened locally by a doubling plate, riveted to the web during the spar construction. This doubling serves to take some of the bearing load of the main attachment bolts from the thin strip steel web and distributes it over a greater length.

Only the horizontal components of the lift and anti-lift wire loads pass into the spar as end load, the vertical component going into the interplane strut by way of the bridge piece. Similarly with the drag wires; the longitudinal component being met by the drag strut itself through the vertical channel and only the lateral component reaching the spar. In the case of the incidence wire, the bridge piece must carry the load.

The wiring lugs and strut attachments must each be designed to take the maximum loads occurring in their respective members. It is frequently the practice to exceed this in the case of wiring lugs. For example, if the load were found to be 12,000 lb., one would choose a

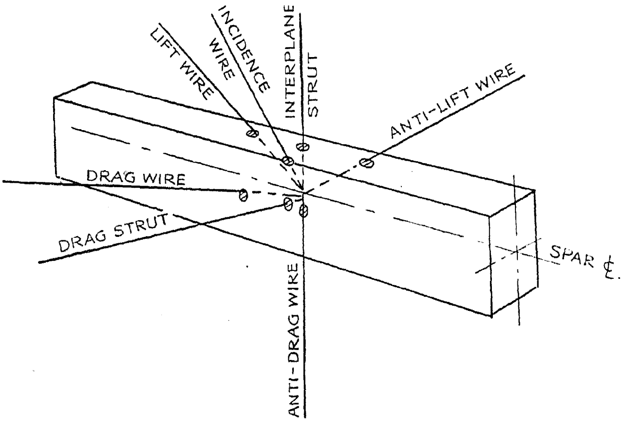


FIG. 43

$\frac{15}{32}$ in. B.S.F. streamline wire or swaged rod to cater for it as being the nearest standard size. This wire has a breaking strength of 13,800 lb., and the lug would be designed for that load, not for the 12,000 lb. actually occurring. There is reason in this lavish treatment, since it may be possible in rigging the machine to put a high initial stress in the wire. But though each attachment should be designed up to the maximum load in the member, the joint as a whole need not be strong enough to take all those worst cases occurring together. The lift and anti-lift wires are not in action at the same time, nor are the drag and anti-drag wires. The incidence bracing, being put in as a "second path" in case of breakage of the lift wire, should not be considered as acting in combination with it unless the structure is being stressed by the Principle of Least Work. For example, the worst case for the joint as a whole may be when the maximum load is reached in the lift wire combined with the load (not necessarily the maximum), which is at that time imposed on the anti-drag wire. Turning again to the joint in question (Fig. 44), it will be seen that the lift wire load is split into the double lugs, half passing down each side of the spar. In this case it would be the horizontal component of the half lift load on the rear face which would be combined with the anti-drag wire load. These questions can be decided only from a detailed consideration of the particular design.

A final point to be considered in such a joint as this is that of offsets. The diagram (Fig. 43) shows the lines of action of the various members all meeting at a point and thus producing an evenly loaded node. When for some constructional reason it is necessary to offset one of the members so that its line of action does not pass through the common point of the others, a bending moment or torsion will be introduced which may cause a big increase in the stresses. Before allowing any such offset, its effect should be very carefully considered. Although the joint as a whole may be balanced and without offsets, the local loads must be catered for. Taking as an instance the anti-drag wire lug, one sees that this exerts a local bending in the near side of the vertical channel against which it beds, and that much depends on the transverse stiffness of the spar, of the drag strut, and of this channel.

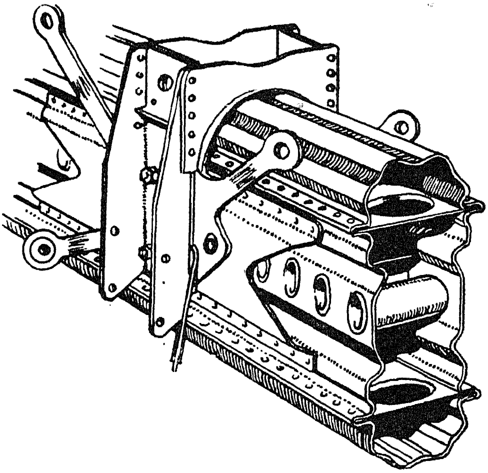


FIG. 44. BOULTON AND PAUL SPAR JOINT

(By courtesy of "The Aeroplane")

The Boulton & Paul joint is built up from high-tensile steel plates riveted together. This accounts for the doubling up of the pin holes in the drag and anti-drag wire lugs in order that there shall be sufficient bearing area on the pins which are of a weaker material.

The method employed in the Fairey type spar for attaching the "N" interplane struts is shown in Fig. 45. The spar itself is stiffened locally by doubling the web plates in the area of the joint, while a rectangular stabilizing box is riveted to the front and the back between the top and bottom flanges. The stabilizing boxes are flush with the width of the flanges, forming a flat base to which the main saddle fitting can be bolted. The saddle fitting wraps over the spar and has welded to it the lugs for the attachment of the interplane struts. Wiring plates for the main plane landing wires are attached to the centre of the joint assembly by a large diameter hollow bolt which passes through the spar web and the stabilizer boxes.

The interplane strut joint on the Fairey tubular spar is also shown (Fig. 46). This is a simple saddle fitting which fits round and is bolted to the spar, the latter being stiffened locally by tubular liner pieces. Distance pieces are used on the bolts whose heads and nuts are shouldered into the spar, providing a large bearing area for the interplane wiring plates which form part of the saddle fitting. The lug for the interplane strut and incidence bracing is welded to the top or bottom of the saddle depending on whether it is an upper or lower plane fitting. The drag strut beds into a socket, which is welded to a plate. This plate picks up the bolts securing the main saddle fitting.

RIBS. Rib construction in wood followed two types, that in which a light girder was built up to the wing contour from thin strips of spruce and that in which the contour was fretted out of a sheet of three-ply suitably lightened with holes. The first was the more popular, being lighter, and the use of the second was principally confined to ply-covered wings. The conventional metal wing has not departed radically from the experience gained with wood, and two corresponding types of metal ribs have been developed. The first of these is built up from small diameter tubes solid drawn or in strip or from channels or some similar section. The second is pressed or stamped from a sheet of metal. Aluminium or aluminium alloy is always used for the second, since sheet steel would be too thin to be stable for a given weight. The built-up girder type of metal rib may be in either steel or light alloy.

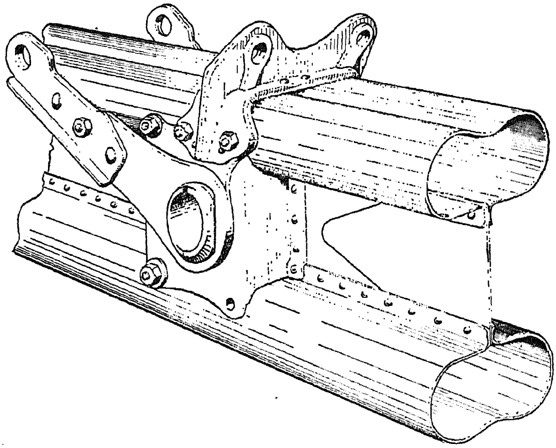


FIG. 45. FAIREY SPAR JOINT
(By courtesy of the Fairey Aviation Co., Ltd.)

Metal, however, was found to give difficulties which were not present in wooden ribs. Owing to the thin gauges imposed by considerations of weight, the bearing strength at the ends of the cross bracings was found to be small. It was impossible to reproduce the large glued surfaces and multiplicity of brads which held the wood together. Vibration, which had created no complications earlier, now caused surprising failures. The difficulties were largely overcome, and a new technique developed. Some manufacturers held to the channel type rib, others to the tubular, whilst some used pressings from sheet. All have their special advantages, but all seem to be equally satisfactory in service.

The stress calculations present no difficulties if the rib be regarded as a pin-jointed structure loaded at each joint. The loads vary according to the wing sections and the two cases of Centre of Pressure Forward

(C.P.F.) and Centre of Pressure Back (C.P.B.) are taken. The fabric pull (due to doping) on the leading and trailing edges applies an end

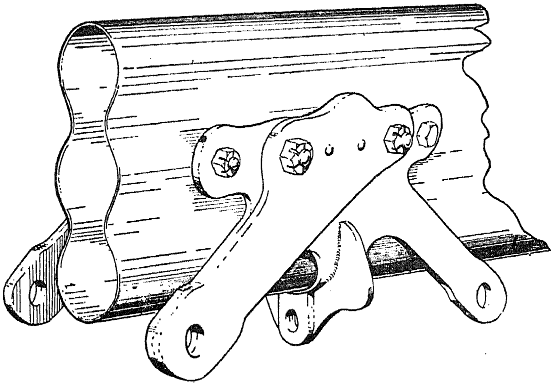


FIG. 46. FAIREY SPAR JOINT
(*By courtesy of the Fairey Aviation Co., Ltd.*)

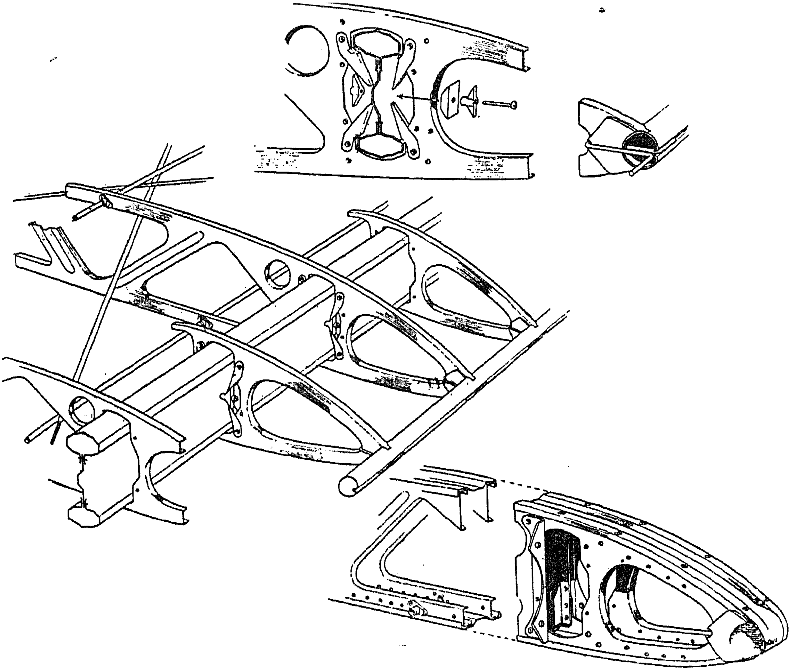


FIG. 47. PRESSED RIBS AVRO TUTOR
(*By courtesy of "The Aeroplane"*)

load to the nose and tip of the rib. This load is dealt with later on p. 71. But, as is the case of a spar, the calculations must be backed up by full size tests, unless the rib be one of a family whose characteristics are well understood. These tests are of two kinds, both of which must be carried out successfully.

The first is static. The rib is attached to stub lengths of spar and gradually loaded up until it carries the full factored load, whether it be C.P.F. or C.P.B., multiplied by the additional load factor of 1·2. If local failure occurs before this load is reached, the test may be stopped and the point of failure stiffened up temporarily. The test may then proceed so that the next weakest point be found. These failures will indicate where further consideration should be given to the design.

The vibration test is more complicated and the requirements are laid down by the Air Ministry according to the type of aircraft on which the rib is to be used. The general scheme is that the rib is set up as in the static test, but, instead of loading it up at every joint, strong attachments are made to both top and bottom booms at two positions between the spars. The vibration is applied to these attachments simultaneously by an eccentric mounted on a rapidly revolving spindle. The test is extremely severe, though possibly not more so than that to which a rib near a wing engine mounting is subject in actual service. There is often some difficulty in catering for both static and vibration tests, the one perhaps suggesting one modification and the other something diametrically opposite. The results are often disconcerting, and it is impossible to generalize. Every design of rib presents its own problems and must be handled accordingly.

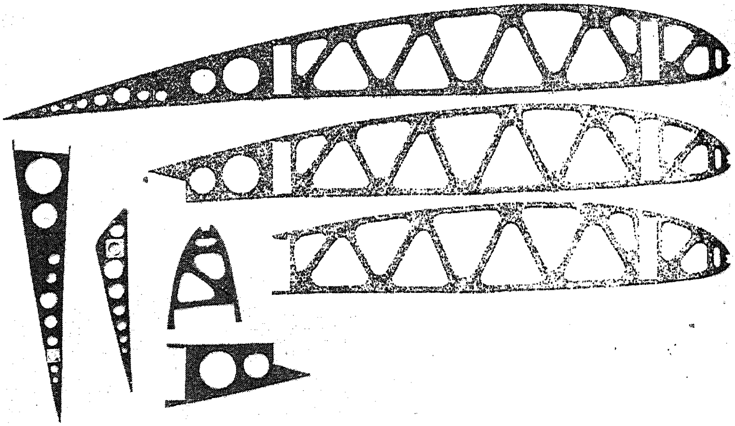


FIG. 48. CURTISS RIBS

(By courtesy of the Curtiss Aeroplane & Motor Co., Inc.)

In the conventional parallel wing it is desirable from a production point of view that all ribs be identical. This kind of wing is usually tied internally with drag and anti-drag wires, and the rib spacing must be such that these wires clear the cross bracing of the rib at every position. Hence the detail design and the spacing are dependent on one another and must be considered together. It is not sufficient to design the rib away from its wing, and hope that it will miss the drag wires in any position. To open out or close up the spacing in order to clear varies the rib loading.

The use of pressings in rib construction has many advantages. The labour charges are much less, and there are no weak spots due to rivet joints where fatigue from vibration may cause sudden failure. The most obvious disadvantage of the pressing lies in the initial cost of plant and the rather elaborate dies which are necessary. There is also a considerable wastage of material in the holes, which are cut out for lightness. The pressed rib is particularly suitable for the plane of constant section where, in large production, the total number of identical ribs may justify the initial outlay.

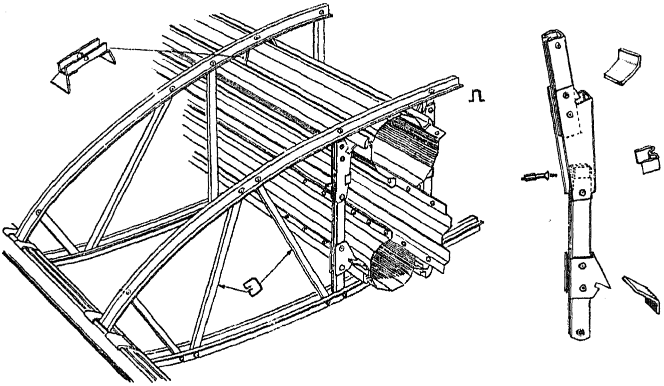


FIG. 49. ARMSTRONG-WHITWORTH RIB
(*By courtesy of "Flight"*)

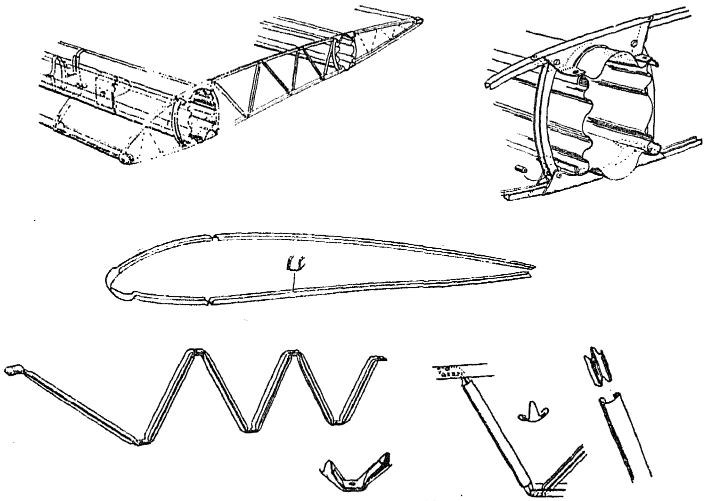


FIG. 50. GLOSTER RIB
(*By courtesy of "Flight"*)

The pressed rib of the Avro *Tutor* is illustrated in Fig. 47.

Triangular lightning holes with flanged edges are stamped out between the spars in such a way as to give a warren girder form. The diagonal slats, thus left, are further stiffened with a shallow corrugation. The rib is attached to each spar by four swinging toggles, two small clamping blocks and a metal thread through the spar web. The leading edge of the *Tutor* main plane is a round tube, along the front edge of which runs a small corrugation. The ribs are attached to this leading edge tube by means of split pins, as shown. Small tubular stringers, from rib to rib, serve as stabilizers. Where a heavy compression rib is required, it is made up from two standard ribs with capping strips, top and bottom. The material of the *Tutor* ribs is aluminium strip to B.S. specification, L.4.

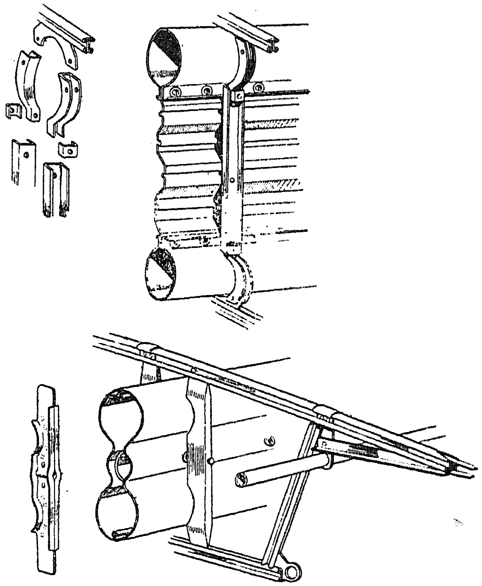


FIG. 51. BOULTON & PAUL RIB CONSTRUCTION

(*By courtesy of "The Aeroplane"*)

A similar rib is used in America by the Curtiss Company on a wide range of their machines. Typical ribs from the Curtiss *Thrush* are shown in Fig. 48. Separate pressings are made for the normal complete rib, short rib in front of the aileron, and nose riblets, etc. The material in this case is Alclad. In Czecho-Slovakia, the Letov Co. developed an almost identical rib for their military biplanes.

The rib developed in steel by Armstrong-Whitworth is shown in Fig. 49, together with the toggle attachment to the spar. The toggle was sprung in and chocked up against the spar after the rib had been held up in position. The square drawn tubes of this rib were all made from strip steel on a draw bench.

The Gloster (Steel Wing Co.) steel rib (Fig. 50) is very simple to make and erect. The sections used are all draw bench work with a small number of pressings at joints. It is adaptable to production and easy to erect.

Another type of strip rib is indicated in Fig. 51, and was developed by Boulton & Paul. The booms were drawn into the form of a T-section with beaded edges. Between the spars, the bracing consisted of small diameter locked joint tubing made from strip. This was similar to that shown in Fig. 244, but on a smaller scale, of course. It was flattened down at the ends and inserted between the double webs of the rib flange.

The material of this rib was stainless steel strip, Specification D.T.D. 158. Electric spot welding was used for making all the joints, and to protect the actual material of the rib itself, each connection was covered with a small strip or doubling. Appropriate methods of attaching the ribs to different spar sections are also shown. On the Mailplane the ribs were of duralumin, but made in similar sections. Electric spot welding was not yet adaptable to this material and riveting was used.

The rib construction of the Fairey *Fox* consisted of duralumin booms, warren-braced with pressings. (Fig. 52.) The boom was of a "double-lobe" section drawn from strip, and similar to the spar flange previously described. The bracing pieces were pressed from duralumin sheet to a trough section. The ends were flattened where they were riveted to the booms. The boom riveting lips were cut away at the spars and aluminium strips were attached inside the booms as stiffening. The rib was fixed to the spars by small plates linking the adjacent web strips to the spar stabilizing plates. (See Fig. 14.)

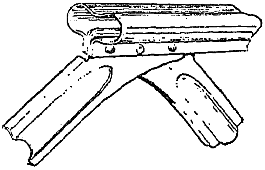


FIG. 52

(*By courtesy of the Fairey Aviation Co., Ltd.*)

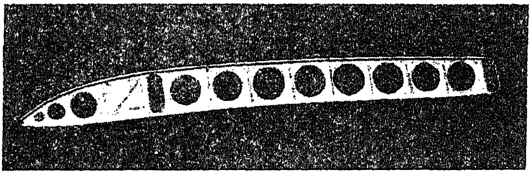


FIG. 53. FAIREY PRESSED RIB

(*By courtesy of the Fairey Aviation Co., Ltd.*)

Another type of Fairey rib, used on the IIIF, Gordon & Seal machines, is shown in Fig. 53. The booms were of the "double-lobe" section described above, but the web was pressed from flat duralumin sheet. This fitted right into the full depth of the booms and was secured by small aluminium eyelets spaced 2 in. apart. At intervals of about 4 in. the web had vertical stiffening flutes, in between which were large flanged lightening holes. The rib had a flanged stiffening plate at the front spar positions where it was secured by a strap clip passing right round the spar. The absence of a tail to the rib was due to there being trailing edge flaps on these machines. The rib ended

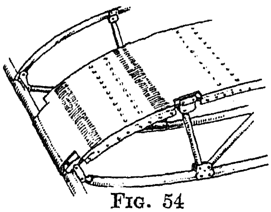


FIG. 54

(*By courtesy of "Flight"*)

at the rear spar round which it was clipped. The top and bottom booms were flattened and bent round the leading edge tube to which they were secured by a hollow rivet.

A completely tubular rib in duralumin made by Vickers at one time is illustrated in Fig. 54. The tubes are all solid drawn, and supplied by the tube manufacturers, requiring only to be cut to length in the aircraft factory. The small clip fastenings between the bracings and booms are standard pressings made from sheet in one operation, and solid snap head duralumin rivets are used. The metal covering shown in this sketch is fitted at such positions as engine walk-ways. Fabric covering is used elsewhere. The same type of rib is also used by other firms, and one from the Supermarine *Stranraer* flying boat is shown in Fig. 55.

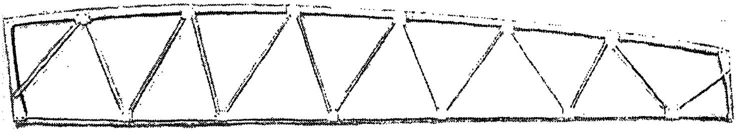


FIG. 55. BOTTOM CENTRE SECTION RIB "STRANRAER"
(By courtesy of Supermarine Aviation Works, Ltd.)

That portion of a wing which has most effect on its lift is the nose between the leading edge and the front spar. The air loading is heaviest here on the upper surface, and, moreover, the steep curvature is liable to cause too much sagging of the fabric and consequently a great departure from the nominal section. It is, therefore, usual to fit riblets in front and on top of the spar. These may be of the same construction as the full ribs and are spaced intermediately. In the slipstream a greater number of these nose ribs are required, and where one only is necessary between each full rib in the outer section, two are required behind the airscrew.

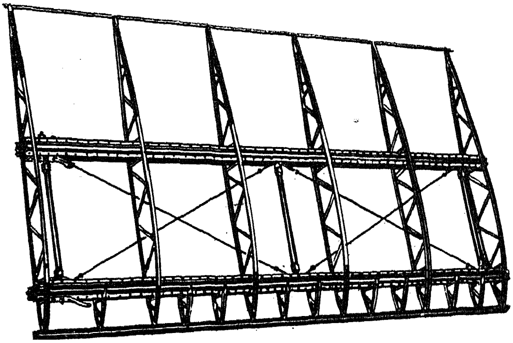
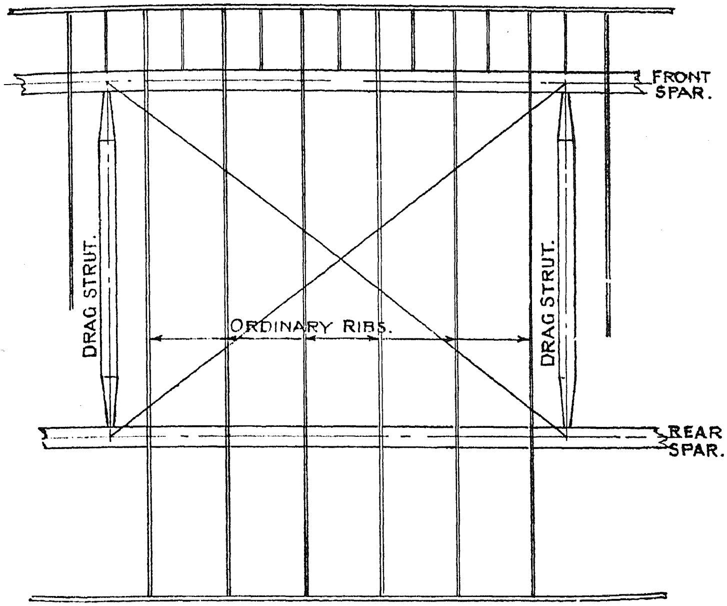
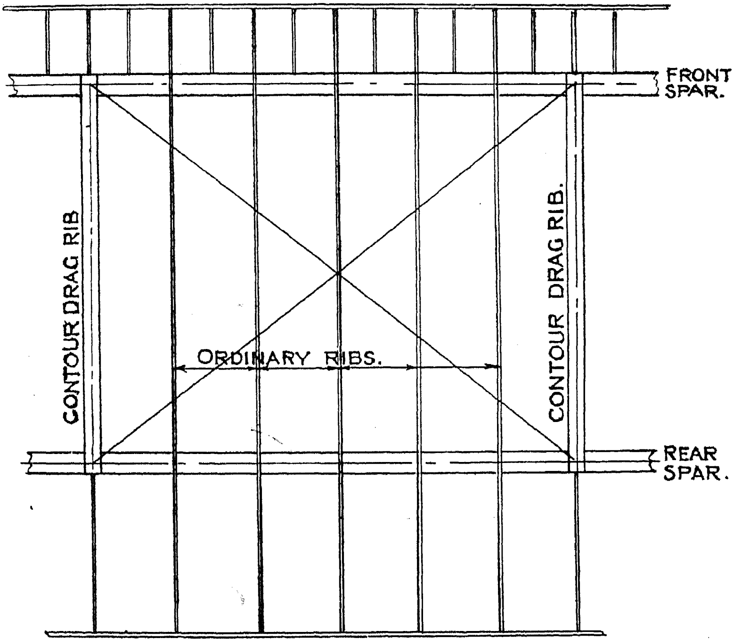


FIG. 56
(By courtesy of "Flight")



FRONT SPAR.
DRAG STRUT.
ORDINARY RIBS.
DRAG STRUT.
REAR SPAR.

Fig. 57



FRONT SPAR.
CONTOUR DRAG RIB
ORDINARY RIBS.
CONTOUR DRAG RIB.
REAR SPAR.

Fig. 58

A complete portion of a main plane is given in Fig. 56. Many of the points in this chapter are here illustrated, including the use of nose ribs and the clearance of the main rib bracings by the drag and anti-drag wires.

RIB SPACING. Rib spacings vary considerably according to the size and type of the main planes on which they are used. The total rib weight may be made less with a wide spacing, but as the fabric sags between the ribs the wing section would be seriously affected. Experience has shown the best compromise to be a spacing of from 12 to 16 in., the bigger spacings being suitable for a total span of 75 ft. or more. This spacing should be reduced by a third on the lower main planes of flying boats and seaplanes.

The question of rib design and spacing is bound up with the design of the planes as a whole, and in particular with the type of drag member. Two kinds of drag members are in general use, the first of which is purely a compression strut, and the second combining a strut in a girder which conforms to the wing section and acts also as a rib. Of these the pure compression strut is usually lighter and cheaper whether it be a simple tube, two tubes, or a built-up parallel girder. Yet if the complete wing design is considered it may be found more economical to use a combined rib and drag strut. An example will make this point clear.

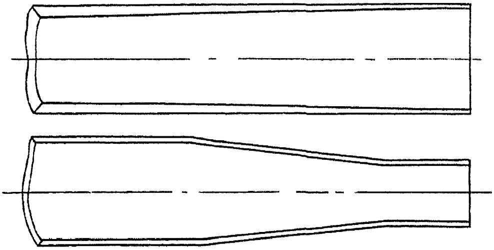


FIG. 59

Fig. 57 represents a bay of the main plane of a large aircraft. In this case tubular steel drag struts were chosen. These, complete with end fittings, weighed 5 lb. each, whilst the ribs weighed 1¼ lb. each. The weight of ribs and struts between the strut centre lines (i.e. half the weight of each strut being included) was 12½ lb.

Fig. 58 shows the corresponding bay fitted with contour struts. These made in duralumin weighed 6 lb. each. But only five intermediate ribs were necessary in this arrangement, giving a total weight of ribs and struts between centre lines of 12¼ lb.

There were twelve such bays in the whole wing structure, and the difference in weight thus amounted to 3 lb. in favour of the type which had the heavier drag strut. And although the contour struts were not only heavier but more expensive in themselves than the tubular struts, the saving in cost of the twelve ordinary ribs which were cut out balanced the account.

Whilst this example may not be true of all designs, it represents an investigation which is worth carrying out. As has already been pointed out on p. 58, the rib spacing will be affected by the drag and anti-drag wires, which must pass through without fouling any of the rib bracing.

It may be necessary to use a second type of rib with a different arrangement of bracing.

DRAG STRUTS. One important aspect of drag strut design has been discussed and the two kinds of strut indicated—the pure compression member and the contour strut.

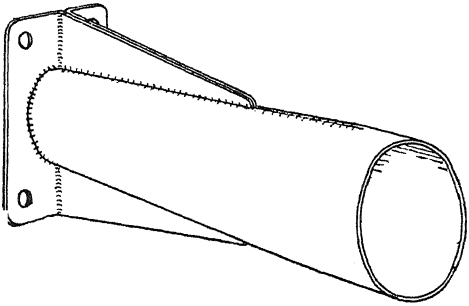


FIG. 60. WELDED END OF DRAG STRUT

The load in the member being known, its design is simple. If a straight, round tube is used, its size may be worked out from the curves in the *Handbook of Aeronautics, Vol. I.* There is little benefit in weight to be had from using high-grade steel or light alloys for this type of member. Steel tube to B.S. Specification T45 is recommended, particularly if the end fitting is welded. Weight may be cut down if the tube ends are tapered. The tube manufacturers will supply the tube reduced either in diameter or in thickness at the ends. They are, however, very expensive. Such tubes are shown in Fig. 59, or the tapering may be done in the aircraft factory by some such method as splitting the end, cutting out a V and closing up with welding (Fig. 60).

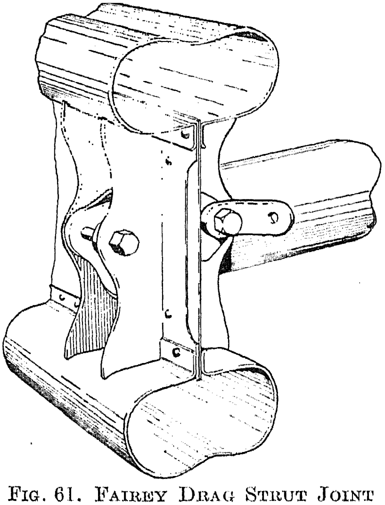


FIG. 61. FAIREY DRAG STRUT JOINT

(*By courtesy of the Fairey Aviation Co., Ltd.*)

The joint of drag strut to a spar of double-lobe section such as the Fairey is done in the manner shown in Fig. 61. The stabilizing plates each side of the spar are of open U-shape, and are riveted to the top and bottom boom webs. The spar web is strengthened with an inserted plate, and the drag strut passes right through this assembly, being bolted through the sides of each U-plate. The in-plane securing bolt also carries the wiring lugs for the drag bracing.

Torsion is induced in the main spars by an overhung aileron hinge or an offset incidence wire. The spar stiffness will counteract this torsion to some extent, but the drag strut which usually comes opposite the hinge or wire may be made strong enough to take the load all in bending. It will obviously have the effect of reducing the compression on one side of the neutral axis of the strut and of increasing it on the other. For this reason, a double drag member is frequently used, in conjunction with double drag bracing. The Air Ministry rules that each wire and strut must be capable of taking two-thirds of the load which the single member would carry. A double strut arrangement is shown in Fig. 62.

An unusual method has been used by Armstrong-Whitworth in which a single tube is offset above or below the centre line of the spars. The torsion of the spar and the additional loading caused in one flange by the drag wire tension must be the subject of detail investigation. A joint and strut of this kind is seen in Fig. 63.

Another type of straight compression member, which is frequently used, is built up of drawn duralumin strip, and is similar in construction to the spars. Compression members of this kind are obviously weaker about the vertical axis than about the horizontal. It is therefore usual to run stringers laterally along the wing to reduce the effective strut length about the vertical axis. These stringers, which may be either struts or ties, must be anchored back to the spars.

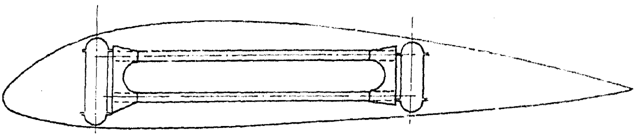


FIG. 62. DOUBLE DRAG STRUT

The greater strength of the member about its horizontal axis helps to counteract spar torsion and contributes very largely to the wing stiffness.

The contour strut is extremely popular, doubtless for the arguments already given in its favour. Two of the actual examples which are available are shown in Fig. 64. The stressing may be done by simple graphical methods. The external forces are the compressive end load which is applied to the booms in proportion to their distance from the drag bracing centre line, and the air load applied to each node as in an ordinary rib. The latter will probably be small in proportion to the end load, but should always be included.

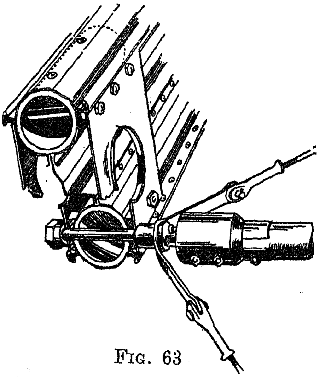


FIG. 63

ARMSTRONG WHITWORTH DRAG STRUT JOINT

(*By courtesy of "Flight"*)

Channels are usually used to build up such compression ribs, and they are corrugated for stiffness. Possible sections are shown in Fig. 65. The depth of flange is governed by the width of material necessary to accommodate the rivets of the cross bracing.

Members of this kind should be given a full scale test so that data may be obtained to back up the calculations, and to discover the maximum stress which is actually being developed. Very interesting results were obtained some years ago when a test of this kind was carried out on a contour rib strut built up of channels to a wing section with a concave undersurface. The strut, which is shown diagrammatically in Fig. 66, was designed to take an end load of 4,500 lb. applied in the line

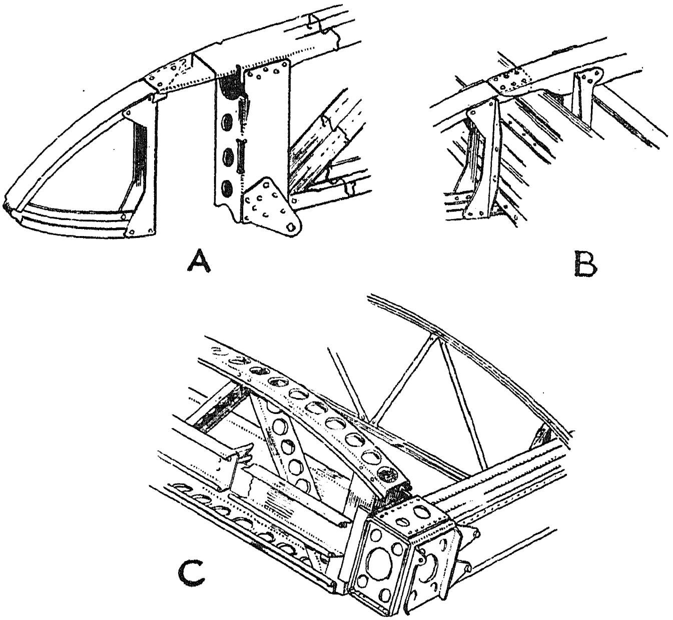


FIG. 64. CONTOUR DRAG STRUTS
A and *B*, Handley-Page; *C*, Boulton & Paul
(*A and B by courtesy of "Flight"*) (*C by courtesy of "The Aeroplane"*)

of the drag bracing. The specimen was loaded up and no failure was apparent when the maximum required figure was reached. The test

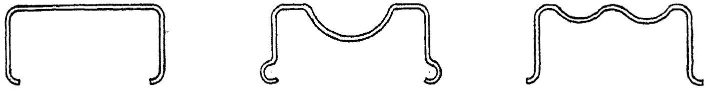


FIG. 65

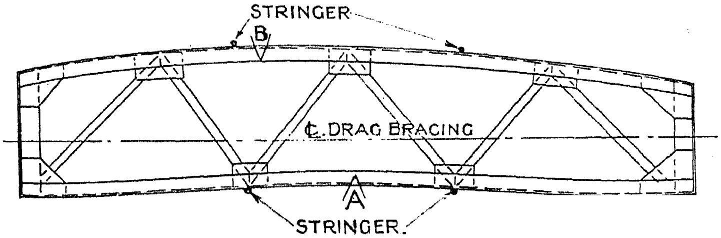


FIG. 66

was, however, continued in order that it might be found how much over strength the member had been. At 4,600 lb. buckling of the channel sides occurred at the point marked *A*. This was to be expected since the eccentricity of the strut as a whole is considerable and the load here higher than elsewhere in the boom. Had the undersurface been convex instead of concave, it is likely that the failure would have been much delayed, the material being disposed further from the centre line. The newer bi-convex wing sections are helpful to the constructional designer in this way.

After chocking up the affected part, the test was continued and failure next occurred at point *B* when the load reached 4,750 lb. Though the load here is less, the material being further from the centre line, the camber of the top surface was sufficient to make each short piece of the upper boom into a bent strut eccentrically loaded.

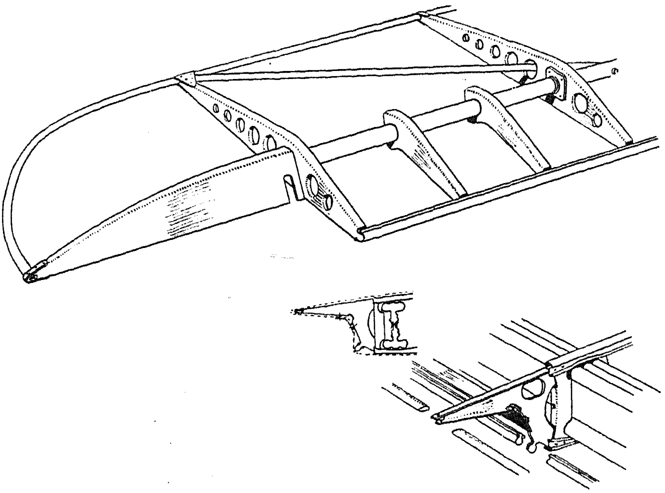


FIG. 67. BLACKBURN "BLUEBIRD" AILERON

(By courtesy of "The Aeroplane")

AILERONS. The method of construction used in the main planes proper is usually continued in the ailerons. This is as it should be, for the problem is the same, and if, for instance, duralumin strip has been decided on for the one, it is obviously the material for the other.

The principal member in normal aileron design is the spar. Since this is not only subjected to bending and shear loads, but also to torsion, a tube is particularly suitable. The torsion applied to it by the operating lever is resisted by the air load on the surface, which is carried back through the ribs. The attachment of the ribs, therefore, must be stout, and not just locations such as are sometimes used at the main plane spars.

A typical aileron, that of the Blackburn *Bluebird*, is shown in Fig. 67, and it illustrates many of the principal points in aileron design. The spar is a tube, but since the surface is balanced, the torsion will be small, probably not much greater than the unbalanced load applied in operating. The ribs are pressed from aluminium alloy and attached to the spar by means of long bolts, which pass through the flanged location plates. The trailing edge is the conventional oval or streamline section tube fastened to the ribs by wrapper plates, and the diagonal member braces the aileron laterally.

The lower sketch in this figure shows how the main plane ribs are ended in way of the aileron, and the small diagram gives the method of holding the fabric into this concave surface.

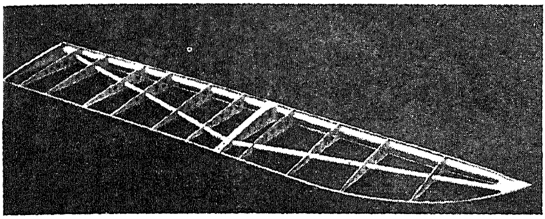


FIG. 68. FAIREY III F AILERON

(By courtesy of the Fairey Aviation Co., Ltd.)

The photograph (Fig. 68) of an aileron skeleton shows a typical form of steel and duralumin construction as used on the Fairey III F. The main spar or hinge tube is of steel and the remainder of duralumin. The lever rib, which is also shown in Fig. 71, can be seen in the middle.

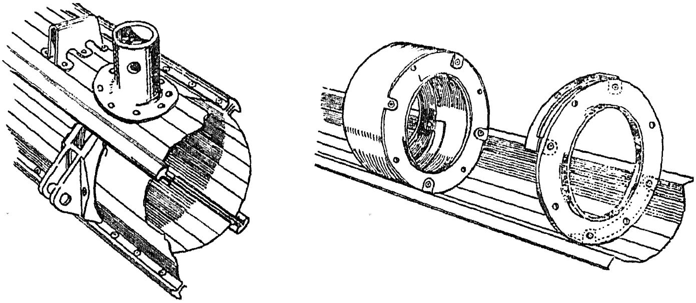


FIG. 69. ARMSTRONG-WHITWORTH AILERON SPAR

(By courtesy of "Flight")

The ribs are fastened to torque tube and spar by means of flanged collars pinned in place.

In these examples the spar tube has been comparatively small in relation to the thickness of the aileron section. It is difficult to manufacture a solid drawn tube of thin enough gauge to allow a larger diameter to be used. And it is doubtful if a purely circular section would be stable in very thin material. A duralumin tube would appear to offer one solution. Another is that shown in Fig. 69 and put forward by Armstrong-Whitworth.

The spar is of a polygon section built up of four drawn steel strips, riveted together with capping pieces over the joints. In this way it is possible to get a light yet stable spar of large diameter. The steel pressings which are used as internal stiffeners are shown on the right. These are fitted at rib positions and behind the hinges, one of which is included in the diagram.

An aileron and a trailing edge flap of Westland construction are shown in Fig. 70. These follow the same principles as the main plane described on page 100. A single channel spar is well lightened with flanged holes and stiffened torsionally with a metal covered leading edge. The trailing edge, which is fabric covered, is carried on flanged plate ribs. At hinge points diagonal tube bracings are put into the panels on each side of the hinge. The end ribs are stiffened against fabric pull by tubes anchored back to strong points on the spar.

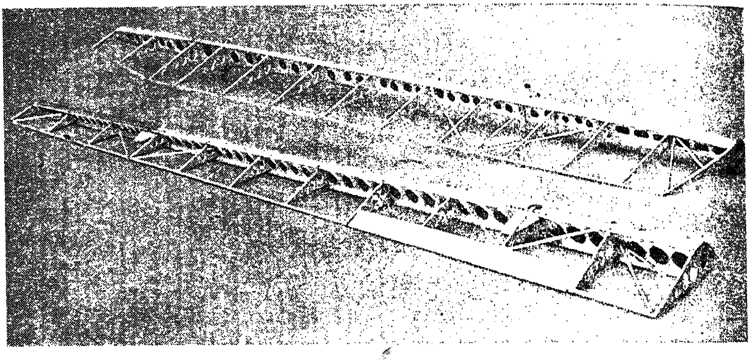


FIG. 70. WESTLAND AILERON
(*By courtesy of Westland Aircraft Ltd.*)

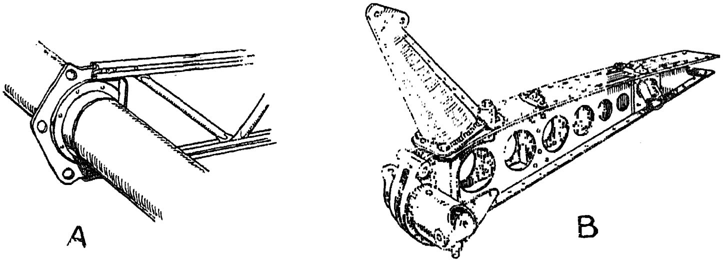


FIG. 71. AILERON CONSTRUCTION
A, Boulton & Paul; *B*, Fairey III F (operating lever)
(*A by courtesy of "The Aeroplane"*) (*B by courtesy of "Flight"*)

A further example is given in Fig. 71. The Boulton & Paul rib-fastening is good, but needs no comment.

An aileron crank and operating rib on the Fairey III F is also included in this plate.

Although welding is frequently used for the tail control surfaces, it is unusual to find it in the ailerons. There is no reason why this should be so, and an example of it is seen in the Curtiss *Robin* (Fig. 72). There is a single tubular spar with the operating lever welded on at its mid-length. The ribs are of small diameter tubing with a single vertical bracing welded in. At the leading edge of the aileron, the rib tubes are bent round and down to the spar, to which they are welded. A vertical support is put in immediately behind the spar. A rib of this sort has taken, on test, a load of 200 lb., whereas the Department of Commerce requirement was only 33 lb.

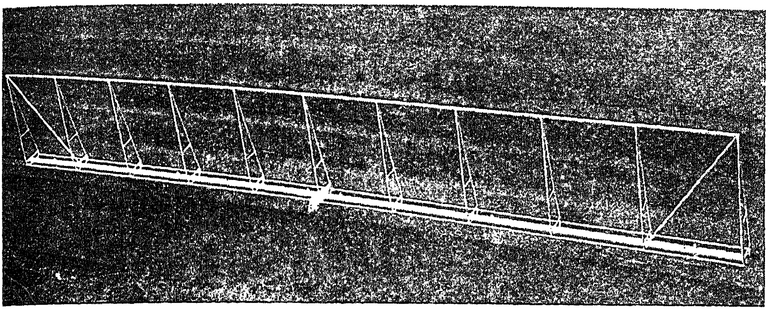


FIG. 72. CURTISS "ROBIN"—WELDED STEEL TUBE AILERON
(By courtesy of The Curtiss Aeroplane & Motor Co., Inc.)

LEADING AND TRAILING EDGES. The leading and trailing edges of fabric-covered wings present little difficulty, and are usually made of tube. Round duralumin tubes of ½ in. to 1 in. diameter are common practice for the leading edge, and a small streamline tube makes a good sharp-pointed trailing edge. (Fig. 73.)

Some manufacturers prefer to use a continuous strip bent round the nose of the wing section, and this method may have advantages for thick or blunt-nosed sections. An example has already been shown in Fig. 40. A leading edge of this kind must be flexible so that it pulls down to the fabric sag. If too stiff it will form a lateral ridge along the wing, with a serious effect on the aerodynamical characteristics of the section.

The tube sizes should be such as to stand a fabric pull of 3 to 4 lb. per inch run, the reactions being at the ribs. This pull should be taken tangential to both upper and lower surfaces, the resultant force being the actual load applied to the tube.

Other illustrations which show leading edges and their attachments have already been given on pp. 57 and 59.

EXTERNAL BRACINGS. Of the wires there is little to be said. They are high-tensile steel of standard streamline section to B.S. Specifications No. W3, fitted with fork ends and lock nuts. The struts, however, are anything but standard, and may be classified as follows—

(i) Round tube;
(ii) Streamline section tube;
(iii) Built up sections from drawn strip.

The same principles apply to the design of round tube interplane struts as to the drag struts already dealt with. They are usually made of steel to B.S. Specifications No. T50 (or to T45 when they have welded end fittings), and tapering of the ends is frequently resorted to.

A round tube is always faired to a streamline shape to reduce resistance. With small tubes up to 1 in. in diameter a tail piece of wood spindled from solid and attached by a spiral winding of frayed tape is sufficient. Such a strut with its fairing is shown in Fig. 74.

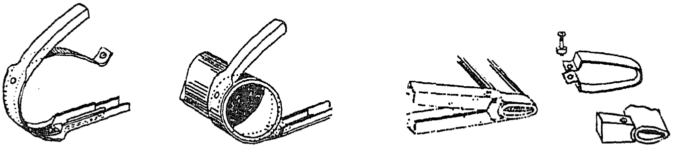


FIG. 73. LEADING AND TRAILING EDGE ATTACHMENTS

(*By courtesy of "Flight"*)

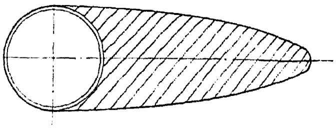


FIG. 74

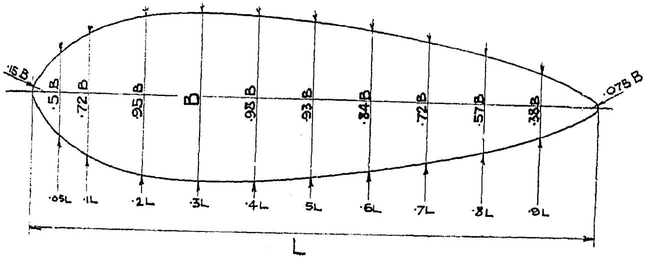


FIG. 75

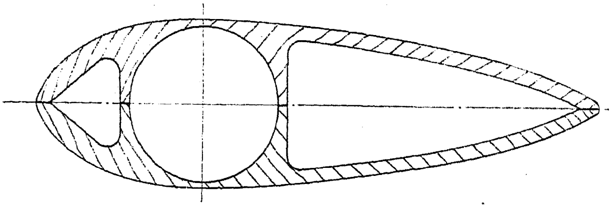


FIG. 76

FIGS. 74–76. INTERPLANE STRUT FAIRINGS

For larger tubes the fairing should be nearer to a pure streamline, and good results are obtained with a fineness ratio of 3½ to 1, the offsets of which are given in Fig. 75. Several methods of attaining this shape are used. It may be made in halves and spindled from solid wood (see Fig. 76), the whole being held together by frayed tape or fabric doped or glued on. This method is inclined to be heavy unless balsa wood is used.

A lighter way is to put ⅜ in. thick spruce formers of the correct contour at 4 in. to 6 in. spacing and to cover with 1 mm. ply, tacked and glued to each former. The whole should be fabric-covered. Continuous nose and tail stringers run the length of the fairing. This method is shown in Fig. 77.

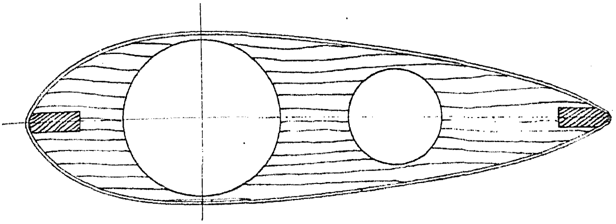


FIG. 77. INTERPLANE STRUT FAIRING

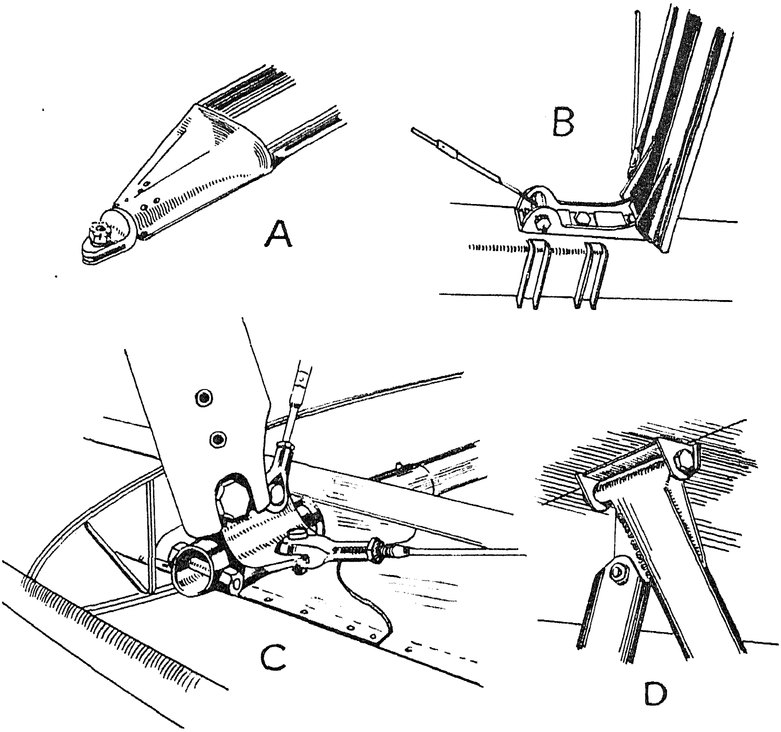


FIG. 78. END ATTACHMENTS OF STREAMLINE TUBE STRUTS
A, Parnall; *B*, Blackburn; *C*, Bristol; *D*, Desoutter
(*A and D by courtesy of "Flight"*) (*B and C by courtesy of "The Aeroplane"*)

Lightest of all is to use a similar construction to the last-mentioned, but to have only fabric covering. In spite of its efficiency, this type is not favoured on account of the ugly sagging of the fabric between the formers.

The end fittings of round tube struts are usually machined from solid bar unless the tube be small, when a welded end may be made up from plate. (See page 356 for typical strut ends.)

The streamline tube makes a very strong appeal for exposed struts, and in small sizes it may be lighter than the round tube with fairing attached. In the larger sizes this advantage is lost, since the strut strength must be taken about the major axis, and much unnecessary weight is carried at the leading and trailing edges where it is of little use.

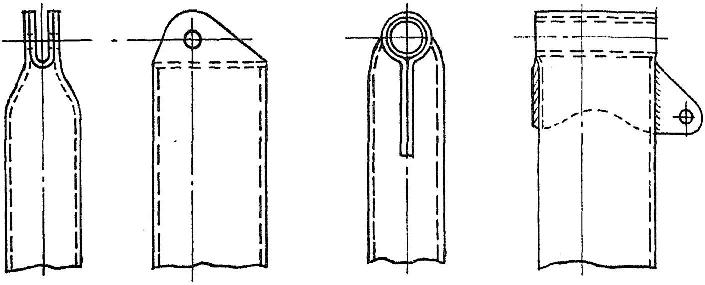


FIG. 79. DESOUTTER STRUT END FITTINGS

The strength may be obtained from Southwell's modification of the eccentrically loaded strut formula. The strut is always assumed to be pin jointed at the ends.

Streamline sections of all sizes and thicknesses are now standardized by the leading tube manufacturers whose catalogues contain useful tables of cross-sectional areas and weights. The radii of gyration of non-circular sections may be found by one of the methods given for corrugated metal spars on pp. 40 and 41. The radius of gyration, $K = \sqrt{I/A}$, where I is the Moment of Inertia and A the cross-sectional area.[1]

FIG. 80

(By courtesy of the Fairey Aviation Co., Ltd.)

Though streamline section tubes are under a disadvantage as struts, they may be used very economically as ties. A particular application is to be found in high wing semi-cantilever monoplanes where they connect the wing to the bottom longerons. Here the only strut loads which they normally carry are the weight of the main planes when the machine is on the ground, usually a quite inconsiderable amount, and the down load which occurs in nose diving.

Different methods of making the end attachments of streamline tube struts are shown in Fig. 78. In the Parnall and Bristol struts a machined end fitting was fastened into the tube by taper pins or tubular rivets. The Blackburn strut end had two saw cuts or slots made across the tube into which plates were inserted and welded. The two different ends used by Desoutter are shown in greater detail in Fig. 79. In each case the tube is split, the one having a distance piece and wrapper plate inserted and the other a U-plate, each being welded in.

Another method of end fixing the interplane strut when the latter is made from streamline tubing is shown in the sketch (Fig. 80). A simple fitting in nickel steel is bent up to slip inside the tube, being then riveted to the tube skin. Side plates are added to the fitting at the pin hole to increase the bearing area. Beech blocks between the fitting and the walls of the tube help to stabilize the assembly.

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[1] *Handbook of Aeronautics, Vol. I,* Tables of Streamline Tube Constants.

In order that there shall not be eccentric loading, it is important that the centre of the end fitting should be over the centre of gravity of the cross-sectional area of the strut. In general this will be nearly one-half of the major axis from the leading edge, but on a long strut its position should be more accurately determined. The method is as follows.

The section is drawn out as for finding the Moment of Inertia (see p. 41) by the method of summation, only the centre line of the thickness of material being shown (see Fig. 81). This line is divided up into short elements a. The distance of each element from the line oo is measured, x, and the distances added together, thus giving Σx. This is divided by the total number of elements in the half section, and the result is the distance of the centre of gravity behind oo. The work may be conveniently tabulated and done in conjunction with the Moment of Inertia calculation.

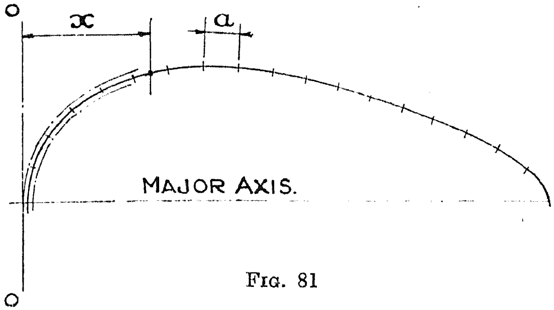

FIG. 81

Round and streamline section solid drawn steel tubes have always been popular on aircraft as external bracings, even when the structure was mainly wood. With the introduction of draw benches and rolls for making corrugated spar and fuselage members in strip metal, it became possible to build up struts and ties to a streamline section by the same methods. Though more expensive to manufacture, these built-up sections can be made lighter and of less frontal area than the corresponding solid drawn tubes. Either strip steel or duralumin may be used, but the latter has advantages owing to its greater thickness and stability on the large radius sides of the strut where the material is most heavily tressed.

A typical strut of this kind is illustrated in Fig. 82. The separate strips are first drawn on the bench and then pulled into one another, an operation for which the draw bench may again be used. The trailing edge (i.e. the back half of the strut) is merely an aluminium fairing, the strength lying in the front half. The universal joint at the end is also shown in the illustration. This consists of an aluminium alloy piece machined from solid and held in channels which, being riveted through large doubling plates, distribute the load over the whole of the effective section.

The strength calculations for a strut of this type should be backed up by a test on one of the actual members in order to find at what point instability occurs.

The strut in question was developed by Handley-Page.

Another drawn aluminium alloy interplane strut is shown in Fig. 83. Used by Vickers on the *Victoria*, this strut sacrificed something in efficiency to achieve cheapness of manufacture. Owing to the instability of thin materials when bent to a large radius, such a strut would not be effective in high-tensile steel. Struts of this material are more elaborate in design, and a typical one made by the Steel Wing Co. (Gloster) is seen in Fig. 84. The front portion is of steel and the fairing of aluminium. The ends are reinforced for the fitting.

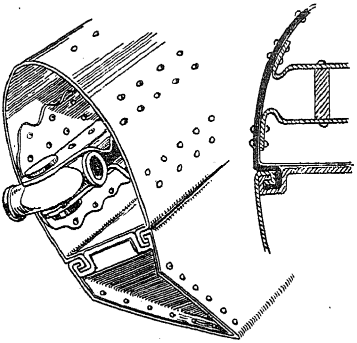

FIG. 82. HANDLEY-PAGE INTERPLANE STRUT

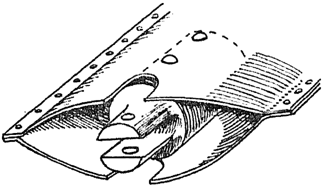

FIG. 83. VICKERS "VICTORIA" INTERPLANE STRUT

(*By courtesy of "Flight"*)

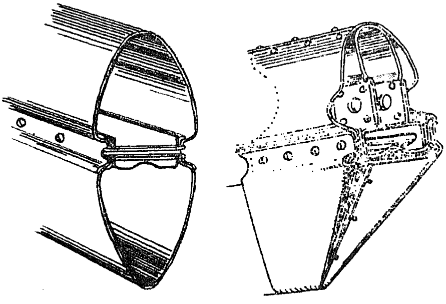

FIG. 84. GLOSTER INTERPLANE STRUT

(*By courtesy of "Flight"*)

Pollard [1] gives some test figures for a strut of this type, not the actual one shown in the above illustration. Designed to a compressive end load of 2,240 lb. and length of 6 ft., the member weighed 3·8 lb. The lightest timber one for the same conditions weighed 6·3 lb., and the best solid drawn streamline tube 4·5 lb.

Another type of drawn or rolled steel interplane strut is illustrated in Fig. 85. This strut has been developed extensively by Boulton & Paul, and the method of manufacture is similar to that of the same firm's well-known closed joint tubing. The two pieces of strip are rolled separately and their beaded edges drawn into one another.

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[1] *Flight*, 31st May, 1928, p. 404*d*.

The joints are made on the minor axis, where normally the stress would be highest and where the large radius of curvature would allow buckles and instability to develop. The beading of this point must have a large stabilizing effect, but no comparative figures are available.

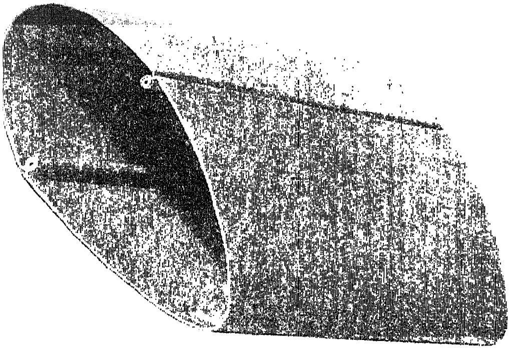

FIG. 85. BOULTON & PAUL—INTERPLANE STRUT
(*By courtesy of Boulton & Paul, Ltd.*)

A built-up strut of a quite different construction was used on the Short *Valetta*, a large high-wing float seaplane. It consisted (see Fig. 86) of a girder riveted up from aluminium alloy flat strip and angles, with a wood streamline fairing added. The use of such a member could only be economical on a large aircraft where the loads are heavy and the struts long. In the more usual sizes a strut of the types already discussed would undoubtedly be more economical.

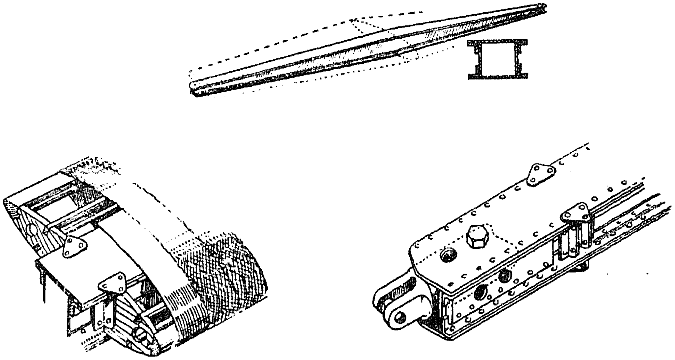

FIG. 86. SHORT "VALETTA" LIFT STRUT
(*By courtesy of "Flight"*)

CANTILEVER MONOPLANES

Although a number of monoplane wing structures have been mentioned in the previous sections, these were fabric covered, two spar, and externally braced planes built in the tradition of the biplane. The growing popularity of the cantilever tapered monoplane coincided with the development of metal construction on a large scale, and many designers saw in the two an opportunity to break away from the classical method. One large school of thought developed the "centre trunk" system described in the introduction to this chapter.

Whilst the reasoning there stated has influenced the design of other methods which are not strictly of the "centre trunk" type, there have been many unique departures from accepted practice. As many as possible of these have been collected and will be discussed in alphabetical order under the different countries of their origin. It is barely possible to group them in any other way since many show distinct originality.

GREAT BRITAIN. **Armstrong-Whitworth.** The basic structure of the Armstrong-Whitworth *Whitley* is a box spar of corrugated aluminium alloy sheet, having great flexural and torsional stiffness. In the centre section it is braced internally by light diamond shaped frames, the apices of the diamond lying at the mid-point of each side of the box spar. The top and bottom apices are carried on fore-and-aft stringers of "top hat" section and a spreader tube runs between them.

The outer sections of the wing taper towards the tips and the box spar becomes of a much flatter section. The internal bracing changes from the diamond construction to something more resembling a conventional rib.

The structure of the centre section is shown in Fig. 87. The leading edge and box spar are covered with smooth aluminium alloy sheet, but the trailing edge, from the rear face of the spar, is fabric-covered.

The metal covering is attached with "pop" rivets by means of a tool such as is illustrated in Fig. 479.

Blackburn. Some years ago the Blackburn Co. developed a single-spar wing construction, designed by the late Mr. F. Duncanson. The spar consisted of a tapered tube of circular cross-section. It was built up of duralumin sheet, supported internally by rings and diaphragms. At the top and bottom the shell of the tube was corrugated to stiffen it in bending, whilst its circular section was ideal in torsion (see Fig. 88).

A portion of the spar was made petrol-tight and used as tankage. This was extremely economical both in space and weight, but implied that the deflection must be made negligible.

Ribs of conventional design ran across the spar, to which they were simply attached.

In some ways the structure resembled that of Kellner-Béchereau (page 138), but there the spar is elliptical in section, and only trailing edge ribs are used.[1]

Bristol. The Bristol Aeroplane Co., Ltd., were pioneers in metal construction and produced a well-known series of all-steel fabric-covered biplanes. More recently they have been equally successful in producing stressed skin cantilever monoplanes.

The structure used in the Bristol 143 and the Blenheim is shown in Fig. 89. The spar flanges are of high tensile steel strip and steel is also used for the heavily loaded fittings. The remainder of the structure, which is more lightly stressed, is of duralumin. Pollard says of

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[1] An early study of the single tube spar, taking both bending and torsion, was made by G. Gabrielli in "Sul Comportamento dei Tubi Sottili in Dural Assoggettati a Flesso-Torsione e Sulle Loro Applicazioni nella Construzione degli Aeromobili," which appeared in *L'Aerotecnica*, Vol. XII, N.12, December, 1932.

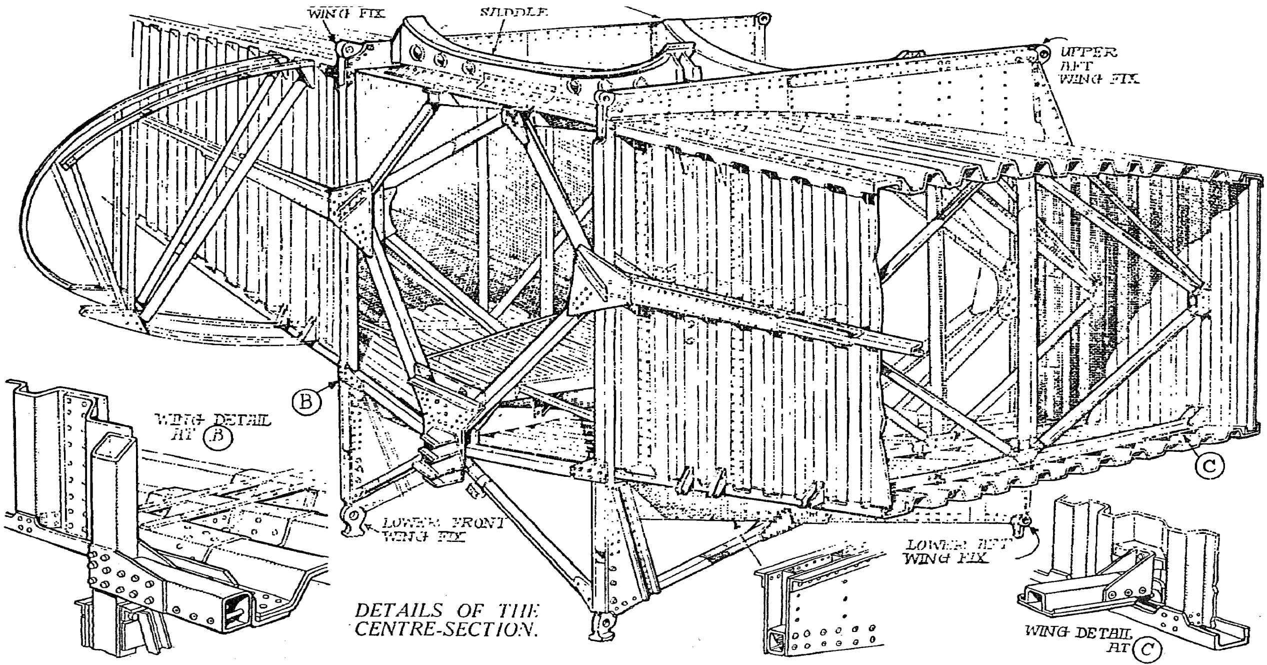

WING FIX
SADDLE
UPPER AFT WING FIX
B
WING DETAIL AT B
LOWER FRONT WING FIX
DETAILS OF THE CENTRE-SECTION.
LOWER AFT WING FIX
C
WING DETAIL AT C

Fig. 87. Armstrong-Whitworth Whitley

(*By courtesy of "The Aeroplane"*)

this structure, "High stresses may be induced in the flanges of a monoplane spar; thus steel can be used to advantage in these cases. Also, the use of steel strip allows of extensive lamination, and variations of sectional area of spar are thus easily possible with attendant constancy of stress intensity."

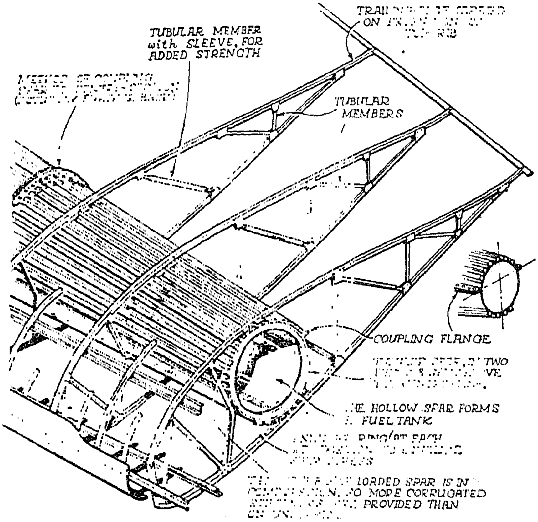

TUBULAR MEMBER with SLEEVE, FOR ADDED STRENGTH
TUBULAR MEMBERS
COUPLING FLANGE
TWO
VE
HOLLOW SPAR FORMS
FUEL TANK
LOADED SPAR IS IN
MORE CORRUGATED
PROVIDED THAN

FIG. 88. BLACKBURN-DUNCANSON WING CONSTRUCTION
(*By courtesy of "The Aeroplane"*)

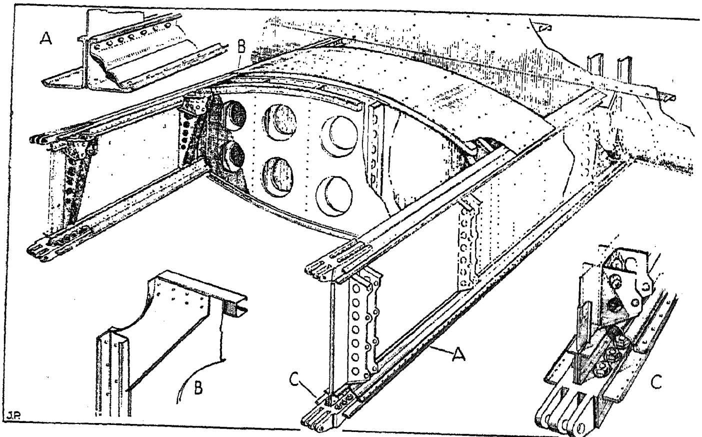
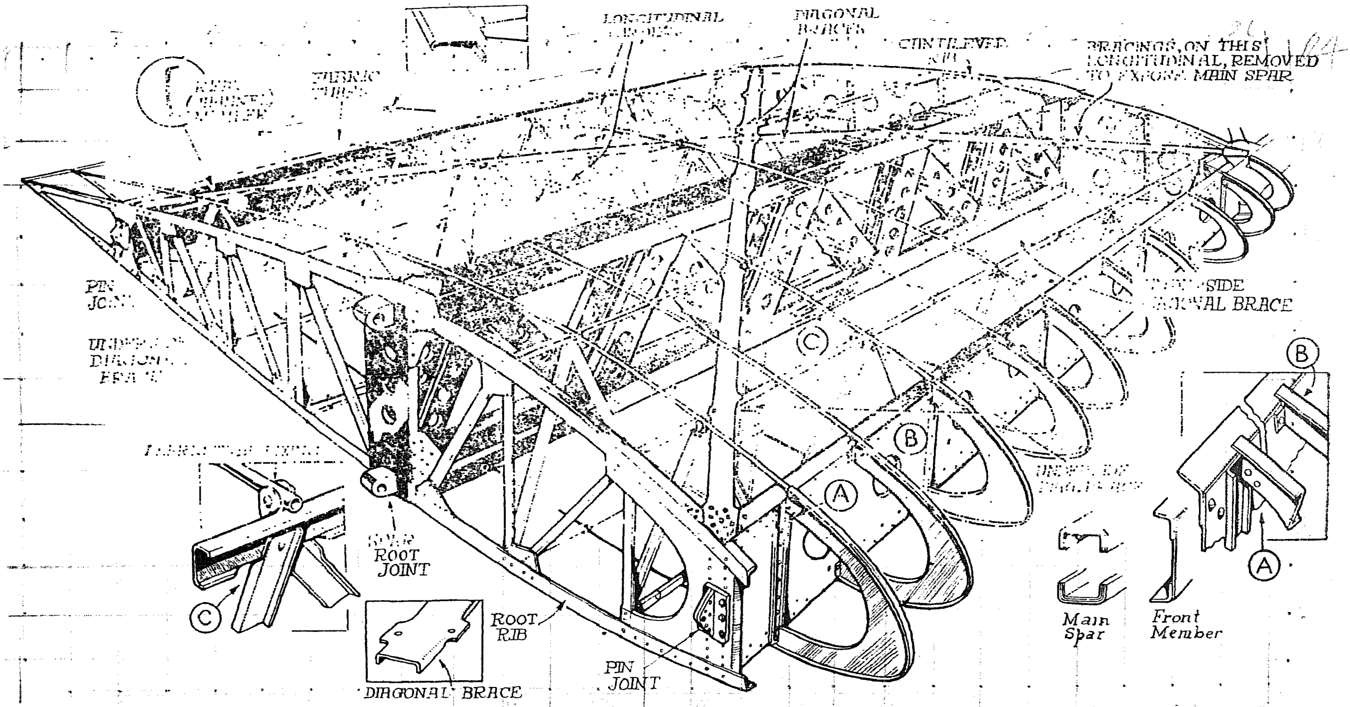


FIG. 89. BRISTOL MONOPLANE CONSTRUCTION

C.L.W. C.L.W. Aviation, Ltd., of Gravesend developed an experimental monoplane wing for which is claimed great stiffness and a considerable saving in weight.



LONGITUDINAL
DIAGONAL BRACES
CANTILEVER RIB
BRACINGS, ON THIS LONGITUDINAL, REMOVED TO EXPOSE MAIN SPAR
PIN JOINT
SIDE
BRACE
C
B
A
SPAR ROOT JOINT
ROOT RIB
DIAGONAL BRACE
PIN JOINT
Main Spar
Front Member
B
A
C

FIG. 90. C.L.W. WING CONSTRUCTION

(*By courtesy of "The Aeroplane"*)

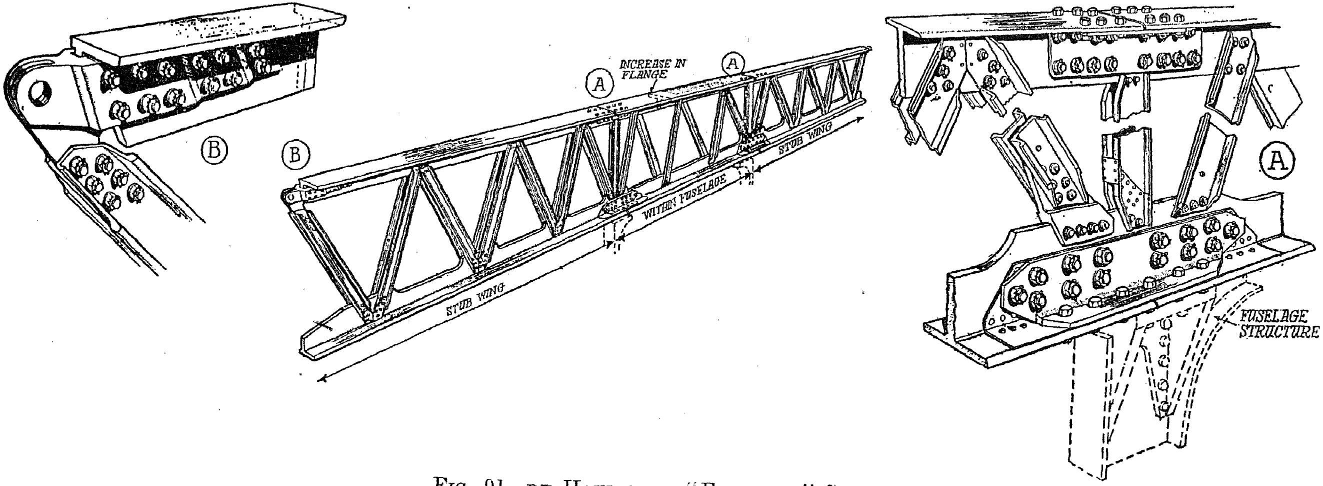

B
B
A
INCREASE IN FLANGE
A
WITHIN FUSELAGE
STUB WING
STUB WING
A
FUSELAGE STRUCTURE

FIG. 91. DE HAVILLAND "FLAMINGO" SPAR

(*By courtesy of "The Aeroplane"*)

If applied to an aeroplane, having a gross weight of 5,600 lb., a wing loading of 19·5 lb. per sq. ft., and a cruising speed of 200 m.p.h., it is claimed that the wing would weigh 1·6 lb. per sq. ft. or 9·1 per cent of the total weight. If these results were achieved in production, the methods of construction would be worth very serious study.

The plane is fabric-covered and torsional stiffness is given by a braced structure independent of the single spar (see Fig. 90). Along the leading and trailing edges run girders which are joined together at intervals by heavy ribs, cantilevered across the spar. The rectangular panels so formed, in plan, are cross braced by diagonal ties of duralumin strip inside both upper and lower surfaces. There are also intermediate light girders running out towards the tip from the inner end.

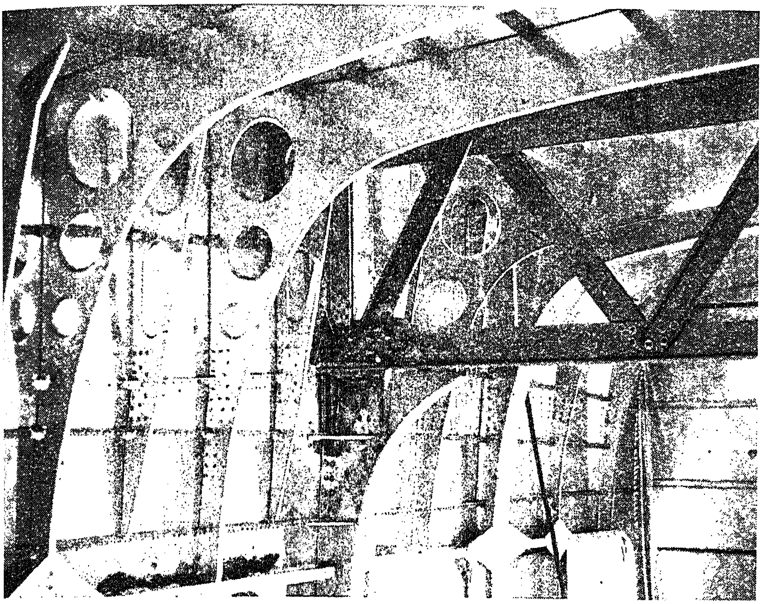


FIG. 92. DE HAVILLAND "FLAMINGO" SPAR JOINT
(By courtesy of "Flight" and the de Havilland Aircraft Co. Ltd.)

Apart from the widely spaced heavy ribs, the wing section is preserved by small duralumin tubes bent fore and aft across the wing and clipped to the main members. Since these can be bent round on the job, they are much cheaper than ordinary built-up ribs.

The spar is a substantial warren girder of duralumin channel sections. It transmits its reactions through robust joint fittings bolted to the upper and lower flanges. The leading and trailing edge girders are pin jointed to the fuselage and are thus prevented from transmitting bending reactions except by way of the main ribs to the spar.

The C.L.W. system could be adapted with slight modification to stressed skin construction if it were found that fabric would not stand the heavy air loads which go with high speed.

de Havilland. The wing structure of the D.H.95, or *Flamingo*, high wing monoplane is based on a single spar. As far as possible, the structure is built up of extruded sections, forgings, and soft-die pressings.

The centre section spar, which extends to the outer sides of the two engine mountings, is a lattice girder of extruded aluminium alloy sections, the flanges of which are of "T" section and the diagonal bracings of channel section (see Fig. 91).

The bracing members are fastened to the vertical web of the flange members by bolts. The top flange of the spar lies just inside the top of the fuselage and the lower flange passes straight across the cabin from side to side, being attached to a heavy fuselage bulkhead by means of a bolted joint and a forging (see Fig. 92). Further details of this joint appear on page 168.

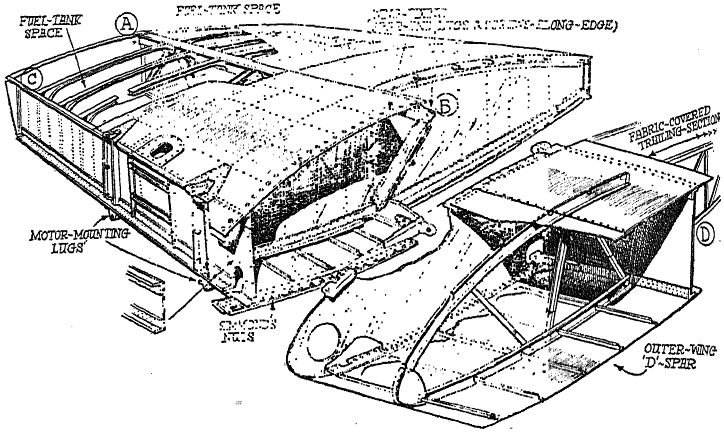


FIG. 93. DE HAVILLAND "FLAMINGO" WING STRUCTURE
(*By courtesy of "The Aeroplane"*)

In addition to this main spar, the centre section has also two auxiliary spars, which carry the leading edge and the flaps. These spars are not built across the fuselage, but join on to heavy fuselage bulkheads at the sides. They are flat plate "Wagner" beams, with extruded angle flanges and vertical "Z" section stiffeners.

The engine mounting lugs on the front auxiliary spar are anchored back on to strong flat plate ribs, which serve in addition to carry the undercarriage loads to the main spar.

The detachable outer wings also have a single main spar but this is stiffened torsionally by the leading edge, and aft of the spar the wing is fabric-covered. Details of the structure are given in Fig. 93 from which it will be seen that the spar is a flat plate girder, having extruded angle flanges. The leading edge is fastened on to the flanges of the spar and the metal covering is supported by heavy channel section ribs, notched to allow the stringers to pass through unbroken.

Behind the main spar are braced ribs of light aluminium alloy sections, those which carry the aileron hinges being of greater strength.

The wing tips are metal-covered and detachable, for ease of replacement in case of damage.

Fairey. The cantilever monoplane wing structure of the Fairey

Battle is almost entirely of aluminium alloy sheet and extruded sections.

It has two spars and is covered with flat sheet which, between the spars, is supported by "Z" section stringers. In the centre section the spars are built-up lattice girders (see Fig. 94) but in the outer wings they have flat plate webs as shown in Fig. 95.

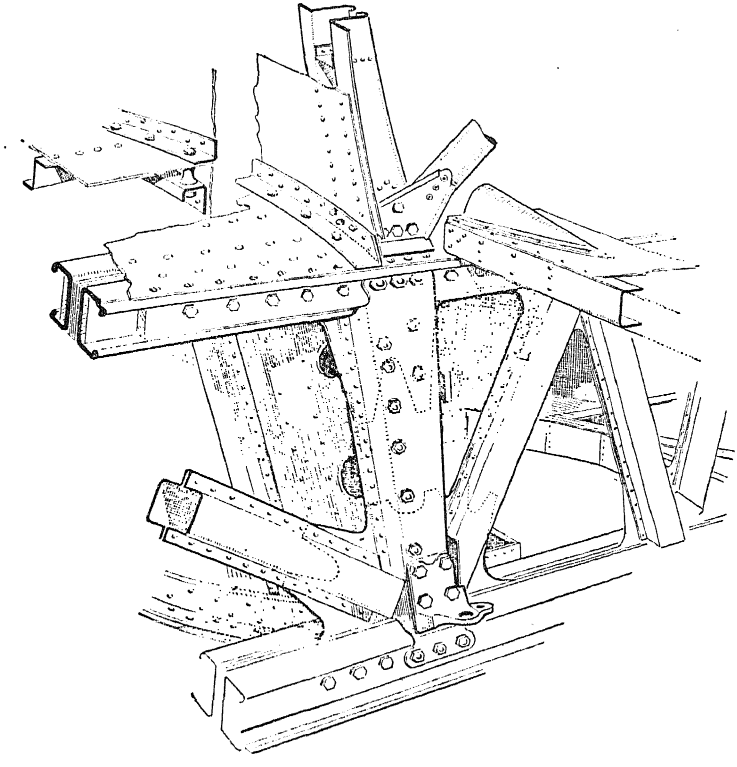


FIG. 94. FAIREY "BATTLE" CENTRE SECTION SPAR
(*By courtesy of "Flight"*)

The spar flanges are of extruded section and the forward pointing lips of the front spar are specially joggled to allow of a flush attachment of the leading edge.

The ribs are flanged pressings from flat sheet, notched to allow the stringers to pass through. Two angle sections are riveted to the rib, one parallel with each of the wing surfaces. The stringers are attached to these by bolts, the bolt holes in the angles being slotted to allow of easy alignment of the stringers.

The spacing of the stringers is 3 to 4 in. and they are parallel. As the wing tapers in plan view the front and rear stringers are cut off as they converge with the spars.

The metal covering between the spars is laid on in strips of about 12 in. width, and riveted. To provide access for this riveting, and also for maintenance in service, one of the lower surface strips is bolted in position, the particular stringers being provided with Simmonds elastic stop nuts. Alternate sections of the leading edge are similarly attached to the spar and fixed sections by these nuts.

Handley-Page. The wing structure of the Handley-Page *Hampden* bomber is unusual and has been designed for rapid production. It is split up into numerous small units which are completed in themselves before being brought together in the final assembly. This allows more labour to be employed without overcrowding and should give easy maintenance and repair.

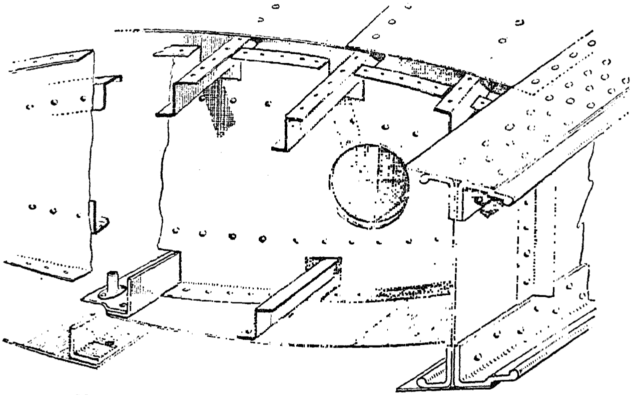


FIG. 95. FAIREY "BATTLE" WING CONSTRUCTION
(*By courtesy of "Flight"*)

The structure of the centre section is based on a single main spar which consists of built-up flanges with vertical and diagonal bracings. These bracings are principally tubular, but at points of high load they are of double channel section. The flanges, as will be seen in Fig. 96, are each built of two extruded "T" sections, side by side, joined across their tops first by a thick strip and then by an outside thin strip to which the skin covering of the wing is attached.

This single spar takes the main vertical bending load on the wing, but is not suitable for either the torsional or drag loads. These are taken by the D-shaped structure forward of the spar, which consists of upper and lower surfaces as far as the false spar to which the leading edge is fastened. The portion aft of the main spar is of light construction, appropriate to the lower loads coming on it.

The outer planes are of similar construction to the centre section, except that the spar has flanges of extruded "L" section, and a flat plate web. The attachment between the outer plane and centre section is made by four bolts, the two principal ones being at the ends of the top and bottom flanges of the main spar. The third is on the front false spar and the fourth lies inside the upper surface near the trailing edge. Their positions are shown in Fig. 96.

A removable panel is provided in the lower surface of the wing to give access to the interior. It is a parallel strip, about 8 in. wide, next to the lower flange of the spar, and it is attached along one edge by means of a wire hinge.

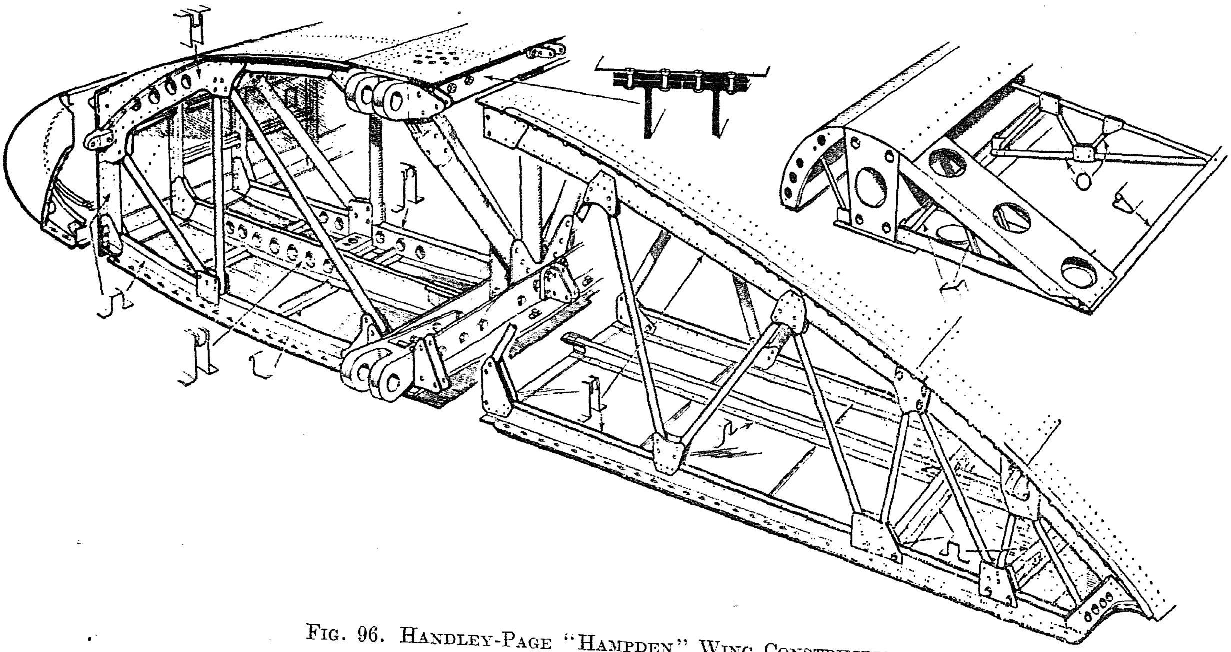
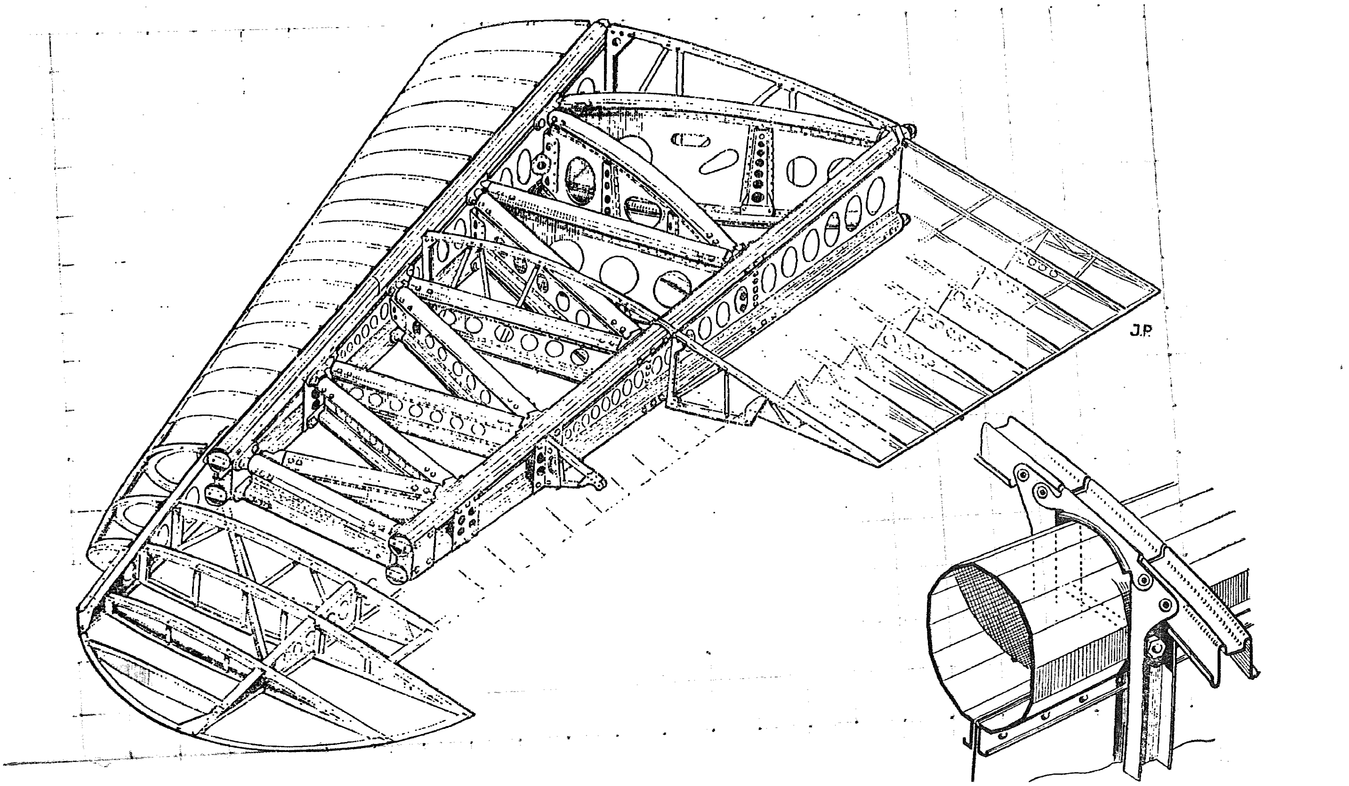


Fig. 96. Handley-Page "Hampden" Wing Construction

(*By courtesy of "Flight"*)


J.P.

Hawker. The cantilever wing construction of the Hawker *Hurricane* single seat fighter monoplane has developed from the earlier biplane structures of such machines as the *Hart.* It bears no structural resemblance to the now conventional stressed skin wings of other monoplanes.[1]

The two spars are of similar design to those illustrated and described on pages 32–4. Since the wing is fabric-covered, except over the leading edge, torsional stiffness must be provided internally. Deep drag members run between the spars of the outer sections, forming a warren girder in plan view. The outer plane ribs are in three parts, one forward of the front spar, one between the spars, and one behind the rear spar back to the trailing edge. A port outer section is illustrated in Fig. 97 and the centre section in Fig. 98.

The details of the structure are full of interest. The spars have polygonal booms of S.88 high-tensile steel strip, but the webs of the outer spars are of flat duralumin sheet. In the more heavily loaded centre section the booms are of double thickness, one lamination being drawn over the other. An internal tubular liner runs from end to end. The centre section webs are of flat steel sheet, stiffened by vertical members riveted on. The steel strip for the booms is received in the final heat-treated condition and after slitting to the correct width it is formed to its final section in a rolling machine.

The outer spar webs are cut on a band saw from flat aluminium alloy sheet. Location holes are drilled, the final edges cut on a router and the lightening holes pressed out and flanged. After setting up the booms and web in a jig, the rivet holes are drilled by multiple head drilling machine. Solid rivets are used for attaching booms to webs. Aluminium castings are fitted inside the booms to stiffen them and act as distance pieces where bolts pass through to attach the end of the diagonal bracing members. The plug ends in these members are machined from aluminium alloy forgings. The more heavily loaded spar end fittings are machined from steel stampings which are subsequently cadmium coated. The large brackets shown in Fig. 98 for the attachment of the undercarriage and fuselage are pressed from stainless steel sheet.

The leading edge ribs are pressed from flat duralumin sheet, whilst the inter-spar ribs are built up from rolled channel section booms of duralumin strip with tubular bracing members. Where the inter-spar ribs are in such a position as to cross the diagonal bracing members they are made up with loose lower booms which are finally fitted on assembly. The inter-spar portions are made short at each end, the gap being normally filled by a 16 s.w.g. washer. The bridge pieces which cross the spar and join the inter-spar to the trailing edge portion of the rib are shown in Fig. 97. They are pressed from thin duralumin sheet.

The leading edge is covered with thin duralumin sheet which extends 2 in. behind the front spar. It is attached to both leading edge and inter-spar ribs by means of pop rivets, the holes for which are drilled on assembly. Except for the panel providing a walkway giving access to the cockpit and guns, the rest of the wing is fabric-covered.

The attachment of the fabric to such a wing presents a problem. In this example, three different methods are used, depending on the circumstances. To attach the fabric to the top and bottom surfaces of the leading edge, strips of duralumin are provided which hold it down on to the nose ribs by means of pop rivets. A covering strip of

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[1] Later "Hurricanes" were fitted with stressed skin wings, but particulars were not available at the time this was written.

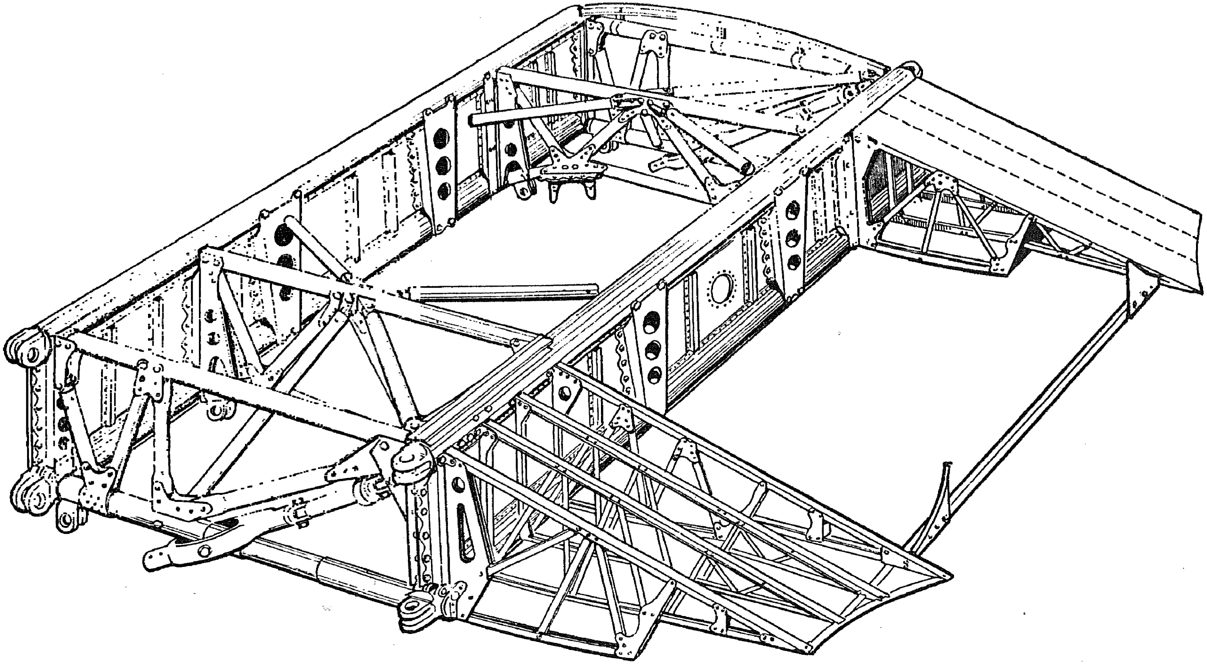

FIG. 98. HAWKER "HURRICANE" CENTRE SECTION

(*By courtesy of "Aircraft Production"*) fabric is doped on. On the outer edge of the walkway panel a wooden strip is fitted to take the fabric.

The method of holding the fabric to the ordinary ribs is illustrated in Fig. 99.

Inside the rib boom are fitted Simmonds anchor or clinch type nuts about 3 in. apart according to the local conditions. A cellophane strip is put over the top of the boom and then a length of Egyptian tape. These are turned down the sides of the channel section and secured by stringing. The fabric wing covering is now put on and tightened down on to the ribs by means of narrow duralumin strips held by Simmonds screws. The recess so formed along the length of each rib is covered by another strip of Egyptian tape, doped on.

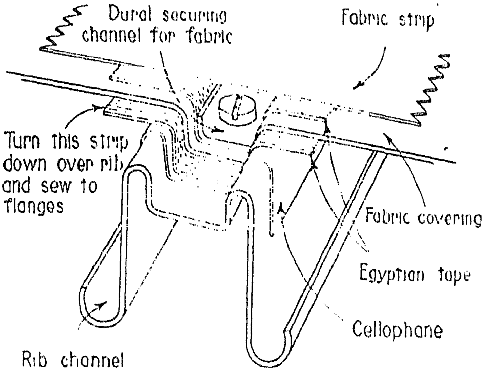
Dural securing channel for fabric
Fabric strip
Turn this strip down over rib and sew to flanges
Fabric covering
Egyptian tape
Cellophane
Rib channel

FIG. 99

Martin-Baker. The Martin-Baker cantilever wing is fabric-covered over ribs which are carried on a single spar. This spar has three booms (see Fig. 101), all of thin gauge large diameter tubes. They are arranged as the corners of a right angle triangle, the third lying horizontally forward towards the leading edge. The three booms taper together as the wing tip is reached and are braced to each other by a system of smaller tubes with flattened ends. The form of joint used for the attachment of the bracings is unusual. A short liner is pushed down the inside of the spar boom so that a hole in the boom coincides with a tapped hole in the liner, the nut for which is brazed to its inner surface. A stud is screwed through the spar into the nut and a saddle washer added outside under the flattened end of the bracings. The joint is then completed with a slotted nut and split pin outside.

The wing folds about the joints of the after pair of booms, the upper hinge being shown at the top of Fig. 100. The lower front boom has a conical turned end which mates with a corresponding socket on the inner side. The screwed pin, which is worked by a handle, passes through the joint horizontally. The incorporation of a jacking pad on the fixed side of the joint will be noticed. It is arranged to cause no offset bending since it lies in line with substantial fuselage members which carry the vertical reaction of the jacking load.

The wing ribs are of the aerofoil section and built up from small diameter steel tubes (Specification T 5) with brazed joints. Clips with suitable flanges are bolted to the spars to carry the ribs, which have small two-hole attachment plates welded in.

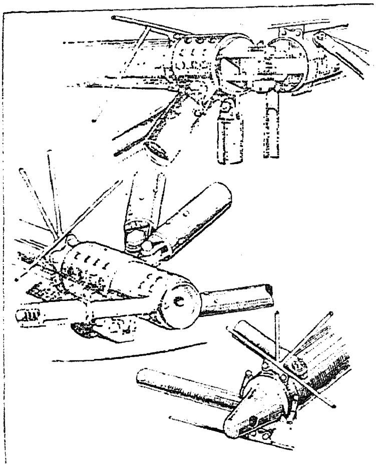

FIG. 100. MARTIN-BAKER WING CONSTRUCTION

(Top) The upper of the two joints about which the wing folds; (below) the two halves of the locking arrangement on the front joint of the wing spar. The screwed pin is worked by a small handle

(By courtesy of "Flight")

This form of structure is undoubtedly very stiff both in bending and torsion. In a design of this sort, however, the bearing stress in the spar tube under the loads from the bracings must be high, since the inner sleeve has only a frictional location. Further, if a fine wing tip were required it would be necessary to design some special extension to the spar booms. Even if the three booms were brought on to one horizontal centre line at the tip the minimum depth of section at this point would be limited by the diameter of the tubes.

Monospar. Although single spar wings have been built by a number of different constructors, the Monospar system is highly original.

The wing is fabric-covered and has ribs of normal design. There is only one spar, and this, of course, carries the whole load. When the Centre of Pressure is directly in line with the spar only flexual bending is experienced. An offset position of the Centre of Pressure results in torque being applied to the spar, which must be

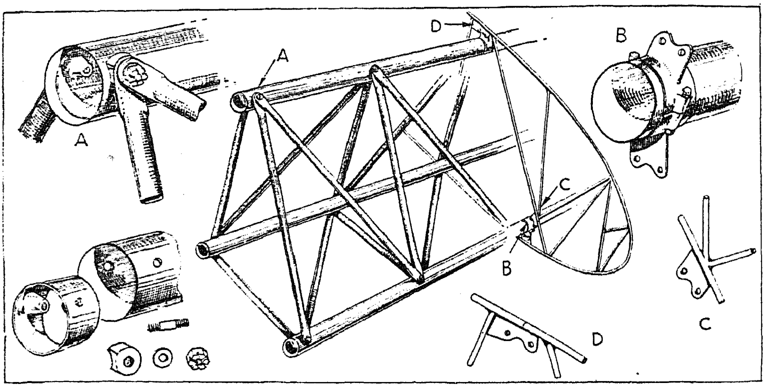

FIG. 101. MARTIN-BAKER WING DETAILS

A set of sketches showing the chief points of interest in the wing spar. The details on the left are of the main strut attachment and on the right of the method by which the ribs are secured. The letters are a key to the details

(By courtesy of "Flight")

stiffened to take it. Pyramids of bracing wires are built off each side of the spar, the apices of which, lying opposite to one another, are connected by means of spreader tubes passing through the spar on its centre line in the fore-and-aft direction. The apices are also connected laterally to provide for secondary flexure.

The pyramid bracing may be regarded as two spiral windings in opposite directions, the one giving torsional strength when the C.P. is forward of the spar and the other when it is behind. An initial tension in the wires may be made to double the torsional rigidity.

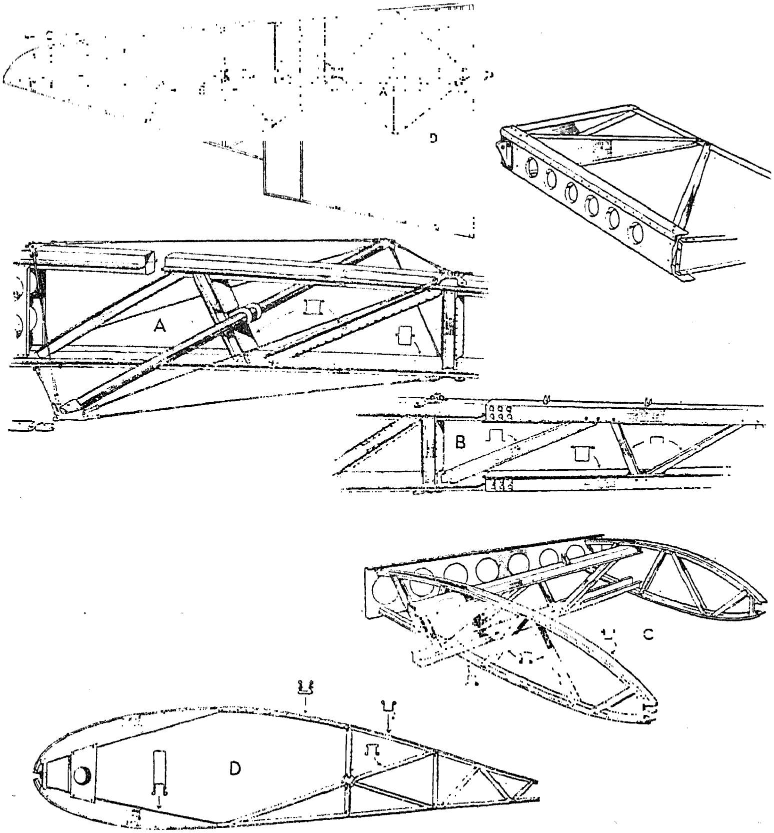

FIG. 102. MONOSPAR WING DETAILS
(*By courtesy of "The Aeroplane"*)

The Monospar system would appear to be most suitable for a thick wing section where the big depth of spar gives an adequate base for the pyramids. The construction, however, is not limited to aerofoil sections with a small travel of the centre of pressure. The bracing system is such that the degree of torsional rigidity is completely under control and can be accurately calculated. Designing to the aerodynamic load for a large C.P. travel would result in a wing of greater rigidity at the cost of a small increase in weight. Recent researches in connection with the flexibility of cantilever monoplane wings indicate specific values of rigidity, and these influence the design of the torsion bracing system in the direction of over-sizing of the bracing if an aerofoil section with a small C.P. travel is used. The end loads in the spar booms due to the torsion bracing system, from aerodynamic considerations, are very small in relation to the main bending loads.

An experimental wing built on this system to fit a Fokker F VIIa-3m weighed 1·3 lb. per square foot against 2·15 lb. for the original ply-covered wing, which latter is of an admittedly heavy and robust construction. Test reports are not yet available.

The system has also been applied to other cantilever monoplanes, including the Monospar 4/5 seater twin engine types, the Monospar S.T. 18-ten seater, and a Saro "Cloud" flying boat.

In the wing of the S.T.4 there are only two bays of pyramid bracing at the inner end. The top left-hand sketch of Fig. 102 shows the general arrangement, whilst *A*, *B*, *C*, and *D* illustrate the points corresponding to these letters on the arrangement. *A* and *B* show the spar construction. This is a simple duralumin girder. The booms are of closed box section, and at each wire joint there is a short vertical. Between the verticals, the spar is diagonally braced with built-up struts. *C* shows the wing tip construction where the main spar and aileron false spar run together. Sketch *D* shows one of the heavier inner ribs cut away to take the petrol tank. The ribs are made of channels drawn from duralumin strip with beaded edges. The remaining sketch illustrates the aileron construction, where the ribs are skewed so that, in effect, they form rigid pyramids which brace the aileron spar against torsion. This spar is a simple built-up channel member which, by itself, would be unsatisfactory in resisting torque.

The fuselage of this machine is similar to the wing structure. A single braced girder runs down to the tail and the cabin structure is merely a fairing, carrying no primary load. The ratio of all-up weight to tare weight of the ST.4 is 1·87, a high figure for a cantilever monoplane. The average ratio for such machines is less than 1·6 (see also Dewoitine, p.125).

Short. For monoplane flying boats and the *Scion* type land planes, Messrs. Short Bros., Ltd., Rochester, have developed a special form of construction. The wing is fabric covered, torsion stiffness being provided by the single spar. This consists of four members spaced roughly as at the corner of a square. Vertical and horizontal separator tubes are put in and the rectangular panels so formed in the top and bottom are each crossed with one diagonal bracing tube. (See Inset.) The vertical panels are wire braced. The continuous corner members are made of extruded cruciform sections in duralumin which lend themselves admirably to the attachment of the gusset plates for the tubular bracings, which are also duralumin.

The wing root joints of the "Scion Senior," a larger monoplane of the same type, are also shown in Inset. In order to give a large bearing surface for each attachment bolt, doubling plates are riveted to the vertical flanges of the cruciform section. They are attached with sufficient rivets not only to take that portion of the bearing load coming into them but also to transmit the reactions from the bracing members attached to them. The economy of material and the extreme simplicity of the joints is particularly noticeable. This wing weighs 1·6 lb. per sq. ft., which is about 11 per cent of the all-up weight of the machine.

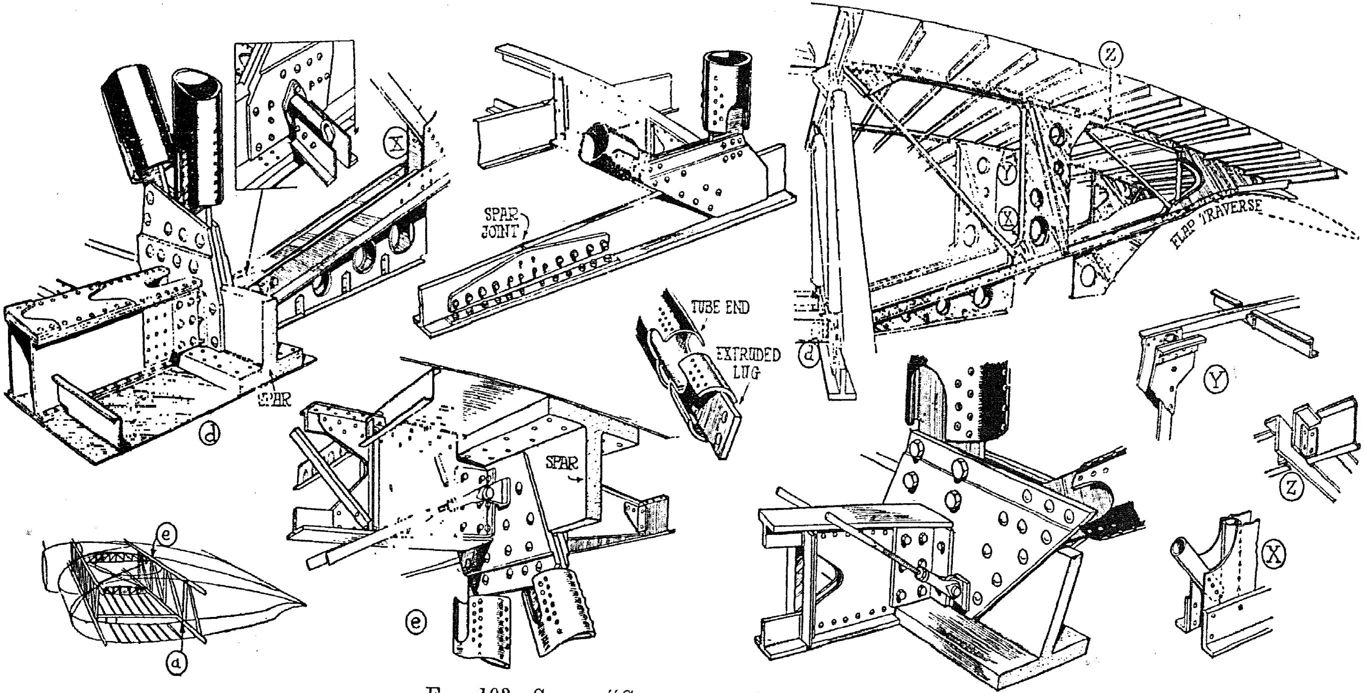
X
SPAR
d
SPAR JOINT
Z
Y
X
FLAP TRAVERSE
d
TUBE END
EXTRUDED LUG
SPAR
e
Y
Z
X
e
d

Fig. 103. Short "Sunderland" Wing Details
(*By courtesy of "The Aeroplane"*)

In the Sunderland flying boat the main plane is similar construction, but metal-covered with thin plating of Alclad Na 23 ST. It is built round a main box spar (as shown in Fig. 103), which consists of two girder members joined between the flanges by heavy fore and aft rib formers and cross-braced in these fore and aft panels by steel tie rods.

The flanges of the girders are made of extruded "T" sections of Hiduminium RR.56, which are machined after extrusion to a slight taper.

The spar girders are braced by vertical and diagonal tubes having extruded end lugs. The form of these is shown in the middle of Fig. 103. They are extruded in long lengths, parted off, and the flanges cut back to leave the web extending as a lug. They are fastened into tubular bracing members by small tubular rivets, and the extending lugs are then held between gusset plates riveted to the vertical flanges of the "T" section spar booms.

This construction should be compared with that of the "Breda 32" on page 148.

Vickers. The Vickers-Wallis Geodetic construction is an attempt to produce a fabric covered structure which will be light and yet have considerable torsional stiffness. The method has been applied to both cantilever main planes and to fuselages. The following description will show its application to planes.

If a bent member is put under compression the ends will tend to approach each other and the amount of bow to increase. But if on the other hand such a member is put in tension it will tend to straighten out. If, then, a rectangular panel under shear is cross braced with two bent members crossing at their mid-points, the additional bowing of the one will be restrained by the straightening of the other. This is, of course, the well-known principle of pyramid bracing with curved, instead of straight, members.

The Vickers-Wallis Geodetic wing has a single spar at about one-third of the chord back from the leading edge. Under the fabric covering lie two diagonal systems of members, curved to the contour, and crossing each other at right angles. If the centre of pressure locus does *not* lie along the centre line of the spar, the wing is under torsion. One system of bracings is thus put in compression and the other in tension.

In its application to fuselages, four longerons may be used and the "Geodesics" or bracing members are spirally disposed in both directions round the inside of the surface.

The calculation of the loads in the geodesics, and consequently their dimensions and most efficient spacing, is extremely complicated. The geodesics may be made up from duralumin channels, cut and jointed at every node. There are consequently a very large number of small pieces which, moreover, are of varying lengths owing to the taper of the wing or fuselage. The additional expense of production must be balanced against a possible saving in weight over the metal-clad structure and the comparison put to the test of commercial competition.

The first production aircraft having a geodetic wing structure was the *Wellesley* single-engined bomber, and this was followed by the heavier *Wellington* which had two engines. In the wing structure of the latter the single main spar was assisted by two auxiliary spars, one in the leading edge and the other supporting the trailing edge flaps and ailerons.

Apart from the detachable tips, the main wing structure is made in four portions, the outer sections joining their respective centre sections at the engine nacelles. The centre sections join on to the fuselage sides, port and starboard, but the main spar protrudes beyond the centre section end rib and the two meet and join on the centre line of the machine.

Thus, the main spar, when joined up, is carried in one piece from wing tip to wing tip, but although it passes right through the fuselage it is not directly connected to it in any way. The centre section end ribs are of such robust construction that they carry the whole lift to the fuselage attachment points of the front and rear auxiliary spars.

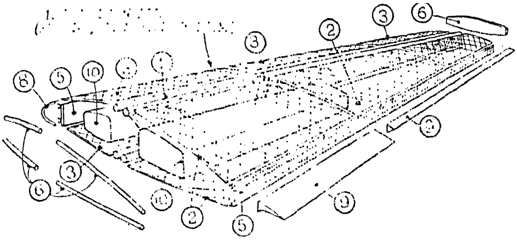

FIG. 104. VICKERS GEODETIC WING
(*By courtesy of "The Aeroplane"*)

In its heavily loaded centre portion the main spar has double tubular booms of small diameter but thick gauge. These are shown in Fig. 105, which illustrates the connection between the main spar and the heavy centre section end rib. This connection is made on the neutral axis of the spar. The same sketch also shows the spar end where it joins the opposite spar on the centre line of the aircraft.

The bracing members of the spar and end rib are all of similar section to those of the geodetic bracing members of the wing and fuselage (see pages 218 and 220).

The heavy tubular booms of the end rib, which pass inside the booms of the spar, meet at the front and rear auxiliary spar joints where all the lift meets its reaction in the fuselage. The joint is shown in Fig. 106.

The pivot fixings at the four joints, front and rear, port and starboard, have thus to carry the whole lift and drag of the wings. The fuselage frame itself appears again in Fig. 254, from which further details will be clear.

The reason for dispersing the lift between the four joints is to prevent the enormous concentration of stress which would otherwise occur if the total lift were transmitted direct from the main spar to a single fuselage frame.

The geodetic bracing panels of the upper and lower surfaces of the wing finish on the heavy centre section end rib. Sheet metal fillets connect this to the geodetic side panel of the fuselage and thus prevent fore and aft movement of the wing.

The booms of the auxiliary spars are incomplete tubes (see Fig. 106), one side being left open to allow of riveting. These spars cannot, of course, carry any bending as they are pin-jointed at their roots. They are subjected only to direct end loads.

The main spar and the front auxiliary spar pass right through the

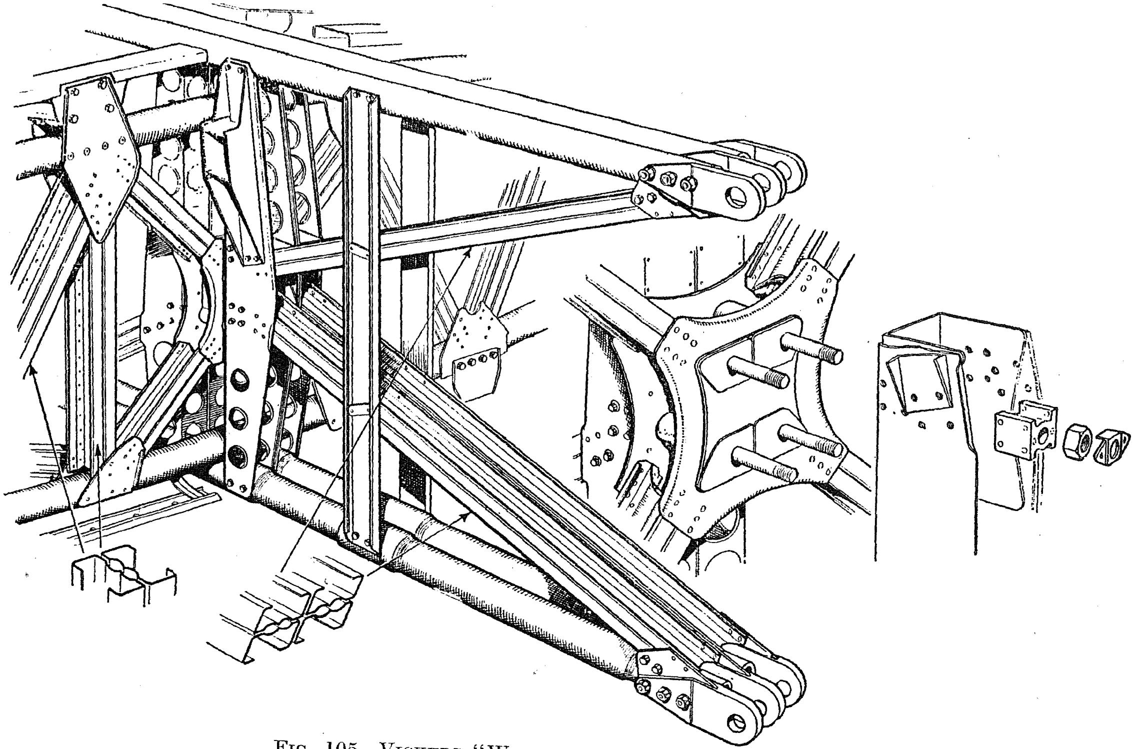

Fig. 105. Vickers "Wellington" Centre Spar Joint

(*By courtesy of "Flight"*)

engine nacelle to joints on the outer sides. The rear auxiliary spar meets its outer extension at the trailing tip of the nacelle.

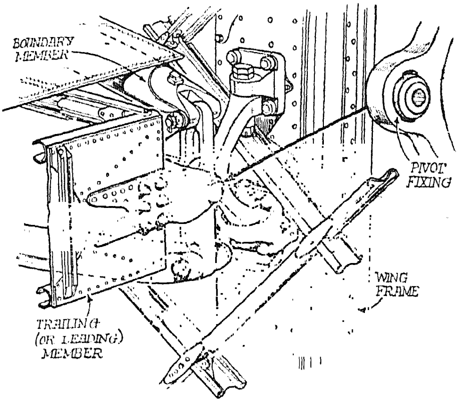

FIG. 106. VICKERS "WELLINGTON" AUXILIARY SPAR JOINT
(*By courtesy of "The Aeroplane"*)

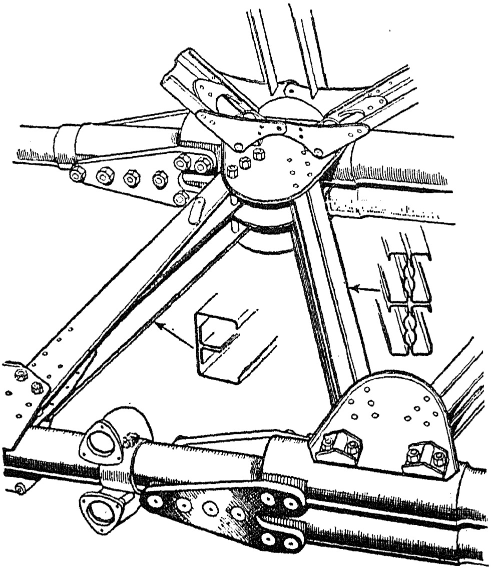

FIG. 107. VICKERS "WELLINGTON" SPAR CONSTRUCTION
(*By courtesy of "Flight"*)

Half-way along the outer wings, the double tubular booms of the main spar are reduced to a single tube (see Fig. 107).

The actual joints between the double and single booms are made with serrated cover plates, the booms being correspondingly serrated.

This figure also shows a joint between the geodetic panels inside the surface. The construction of the wing panels is similar to that of the fuselage panels appearing in Figs. 254 and 255. As will be seen from Fig. 104 the complete half wing is covered by twelve panels, meeting at the spars. They are assembled complete with undoped fabric covering, the final doping and painting being done after final assembly of the wing.

The method of attaching the fabric to the geodetics is shown in Fig. 108. Wires are threaded through drilled bolts which pass through the flange of the geodesic and the whole is covered with serrated tape. A tape is also put in under the wire to prevent chafing of the fabric.

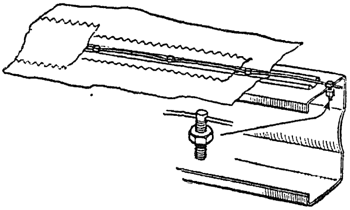

FIG. 108

(*By courtesy of "Flight"*)

The interior of the geodetic wing is completely clear of bracing members, all the loads being carried by the spars and covering panels. This allows ample room for the tanks. At the same time continuity in the panels is very necessary and therefore the fuel tanks are slid in from the inner end of the wing. Three tanks are made up in the form of a train, connected together, and there are two such trains, one on each side of the main spar. They slide in on wooden rails. It may appear difficult to change tanks if a leak occurs, but it is claimed that a wing can be taken off a *Wellington*, a train of tanks changed, and the wing reassembled in 2½–3 hours. The total quantity of fuel which may be carried inside the wing of a *Wellington* is 750 gallons.

It has been shown that considerable damage may be done to the geodetic structure without the safety of the aircraft being endangered.

Westland. The monoplane wing construction developed by Westland Aircraft, Ltd., is of the single spar type. As in others of this type special measures are taken to provide for torsion, the single spar being designed to carry the bending load.

This spar (Fig. 110) is situated at one-third of the chord behind the leading edge. It is built up of top and bottom booms of extruded aluminium alloy sections, connected by a single plate web to which are riveted vertical stiffeners. The extruded section booms are machined to preserve a uniform stress throughout their length. At the bolted attachments of the tubular drag struts a block of metal is left unmachined from the extrusion to take the localized bearing stresses.

To the forward face of the spar are attached diaphragm formers spaced some 12 in. apart. To these and to the spar is riveted a skin covering which is assembled in over-lapping panels of the same width, the riveting being completed panel by panel so that access is always available from the open end of the sheet which is being worked on. In the portion of the wing shown in Fig. 110 can be seen the way in which the leading edge is shaped to take a Handley-Page slot.

Whilst this metal covered leading edge forms a "tube" which is stiff in torsion, the wing is also stiffened by a series of tubular pyramids attached to the back face of the spar (Fig. 109). These also serve to carry the drag load since the apices of the pyramids are joined by a strong tubular member. It will be seen that this is in compression under the backward component of the lift. Where an aileron or flap hinge occurs it finds a strong attachment point in the apex of one of the pyramids.

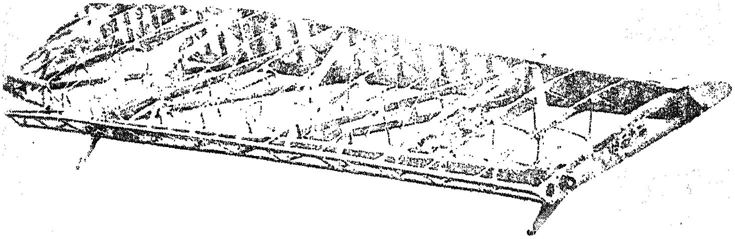

FIG. 109. WESTLAND WING CONSTRUCTION
(By courtesy of Westland Aircraft Ltd.)

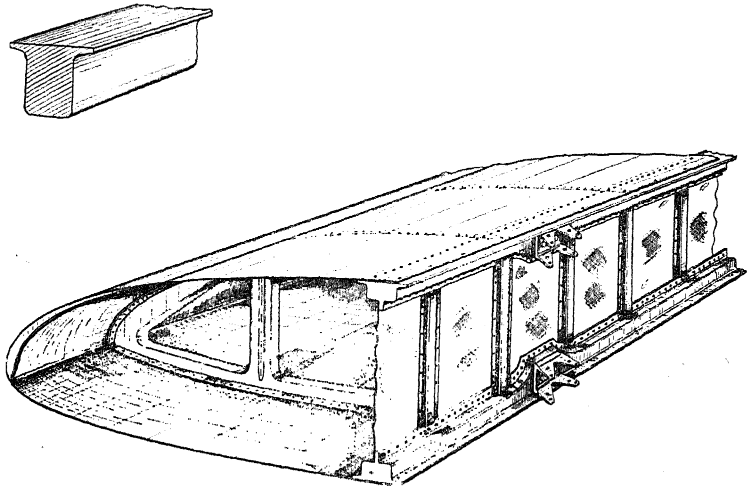

FIG. 110. SPAR CONSTRUCTION OF WESTLAND MONOPLANE

The after part of the wing is covered with fabric, light tubular duralumin ribs to support this being attached to the spar and to the rear transverse tube. It will be seen that these ribs and the diaphragms on the front of the spar come opposite to vertical stiffeners on the spar web.

Heavily loaded monoplane wings used on high speed aeroplanes have given considerable trouble when covered all over with fabric. The suction over the top of the leading edge is particularly high and results in the fabric billowing out between the ribs unless these are very closely spaced. A metal covered leading edge overcomes this trouble, particularly if it is used to give structural strength as well.

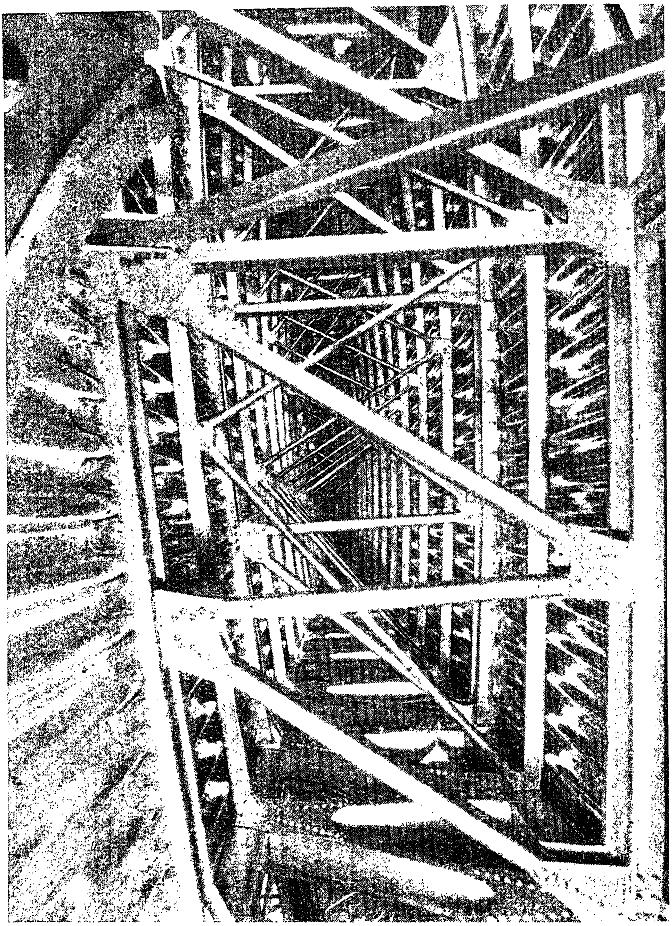

FIG. 111. BOEING WING CONSTRUCTION
(By courtesy of the Boeing Aircraft Company)

It is of interest to compare this construction with that of the Dewoitine D 332 shown on page 127.

AMERICA. **Boeing.** The Boeing Aircraft Company have designed and built a considerable number of large aircraft. They have developed large cantilever wings over a period of years and produced very satisfactory results, the structure having two truss type spars built up of tubular members.

The outside flat sheet metal covering has, between the spars and over the leading edge, an inner skin with corrugations running from tip to tip. The trailing edge behind the rear spar is covered either with flat sheet or fabric. The ribs are of channel section with tubular truss members. These points are clearly brought out in Figs. 111 and 112.

The use of double skin coverings, the outer one flat and the inner one having span-wise corrugations, is common in America, and will be found in a number of succeeding examples. The inner corrugated skin helps to resist bending moments and adds to the torsional stiffness of the wing as a whole. In this connection a publication of the Boeing Company[1] is of great interest, an extract from which is given below—

> "The first impulse of the Designer who is well versed in his monocoque design is to use skin or covering as thin as possible, as the best strength-weight ratio is thereby obtained. However, tests have shown that this is not always the best practise. For instance, torsion tests on cylinders constructed of corrugated and flat sheet have shown that corrugations are only about 50 per cent as effective in resisting shear as the skin. Thus, in a wing where high torsions exist, the choice of skin thickness should not be too low, as material is simply needed to resist shear and the skin provides the most efficient medium. Also the amount of wrinkling permitted in the skin when the corrugations deflect elastically under compression loads is important. Too thin a skin will give excessive wrinkles at low factors. The conclusions drawn, as a result of the cylinder tests mentioned and certain wing tests, are that with skin of a thickness equal to approximately half of the corrugation material thickness, there need be, in the usual wing, no worry about the effects of torsion or of local wrinkling at low factors."

On the subject of the truss type spars built up of tubular beams they say—

> "In this connection it should be noted that the tubes used are of square, rectangular, and barrel section, the latter having two flat sides for ease of attachment and two rounded sides to give high compression strength. The advantages claimed are—
>
> (1) The minimum weight for very deep spars with high shear loads is obtained.
>
> (2) Webs subject to local or general wrinkling are avoided. For light weight, "I" beams must necessarily have thin webs (Wagner beams) and these may be subject to undesirable wrinkling at low factors.
>
> (3) Greater inspection facilities, particularly when removable leading and trailing edges are used.
>
> (4) Tubular members have inherently high local crushing strengths. This feature and their essential character of compactness permit the use of members of minimum external dimensions.
>
> (5) Tubular members are well adapted to the use of high strength steel (180,000 lb. per sq. in. tensile strength) and 24 SRT aluminium alloy.

---

[1] "Problems in the Design and Construction of Large Aircraft," by R. J. Minshall, J. K. Ball, and F. P. Laudan, presented to the National Production Meeting of the Society of Automotive Engineers at Los Angeles, October, 1936.

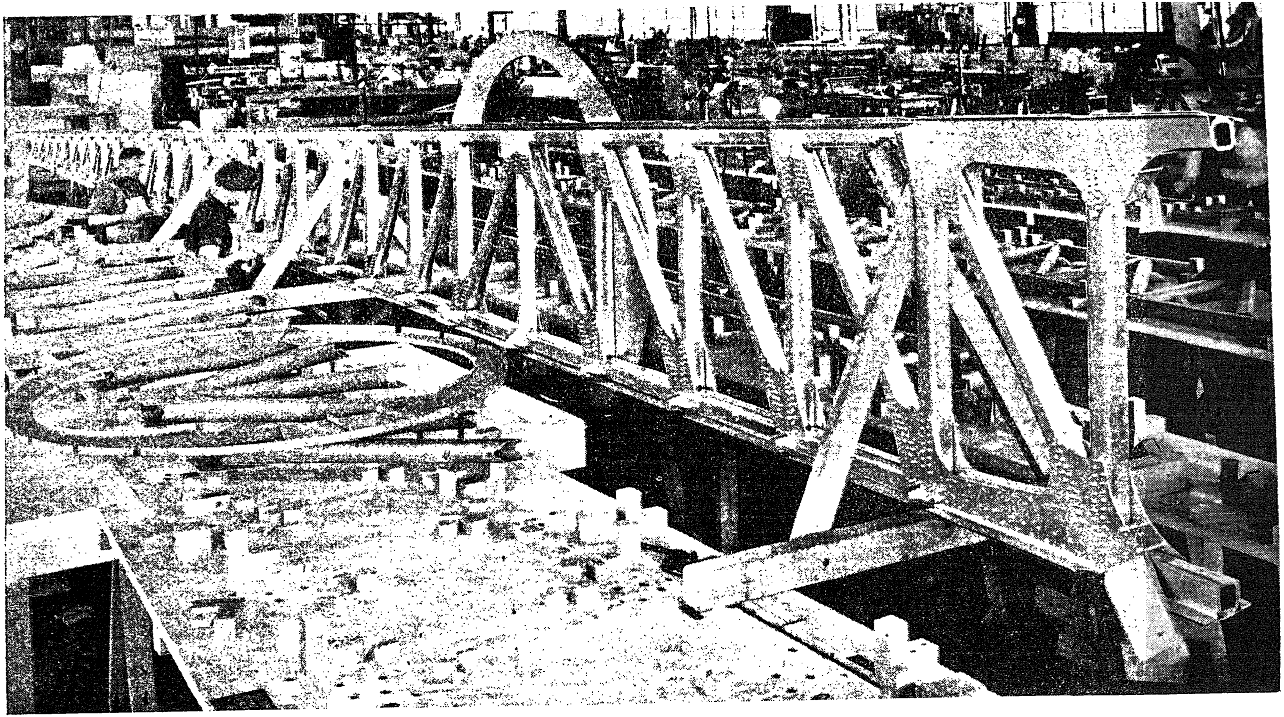

Fig. 112. Boeing Wing Spar

This truss-type wing spar photographed inside the Boeing Aircraft Company plant at Seattle forms part of the framework of the wing in Pan-American Airways 41-ton Boeing transoceanic flying boat. The wing measures 152 feet from tip to tip

(By courtesy of the Boeing Aircraft Company)

(6) The tubular sections used (by reason of their shape) permit ease of attachment with adjacent parts."

Fig. 113 shows a typical gusset joint such as is used to attach a heavily loaded compression strut to the lattice spar of a large Boeing wing.

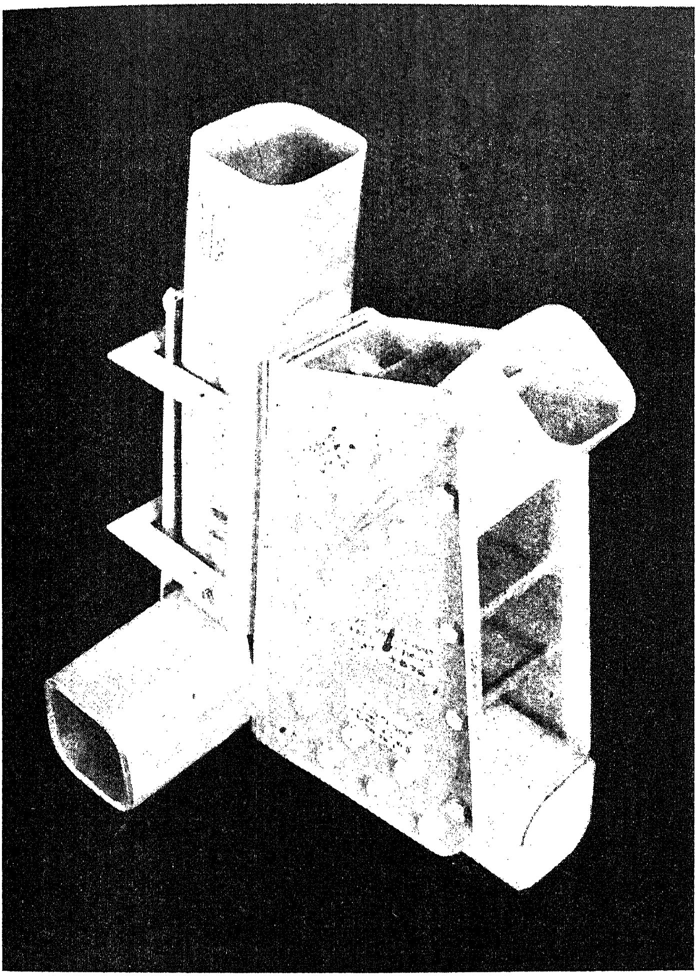

FIG. 113. TYPICAL U GUSSET
(*By courtesy of the Boeing Aircraft Company*)

The outer flat skin is spot welded together into long lengths. It is then mounted on a large reel and passed through the anodizing bath in sections, as will be seen in Fig. 114.

By this method much time is saved and the cost of the metal covering by no means as great, at least in labour charges, as if mounted on the wing in individual sheets which are separately treated. Great care, however, is necessary so to design the curvature of the surface that no double curves are introduced which would cause ugly bucklings in the skin.

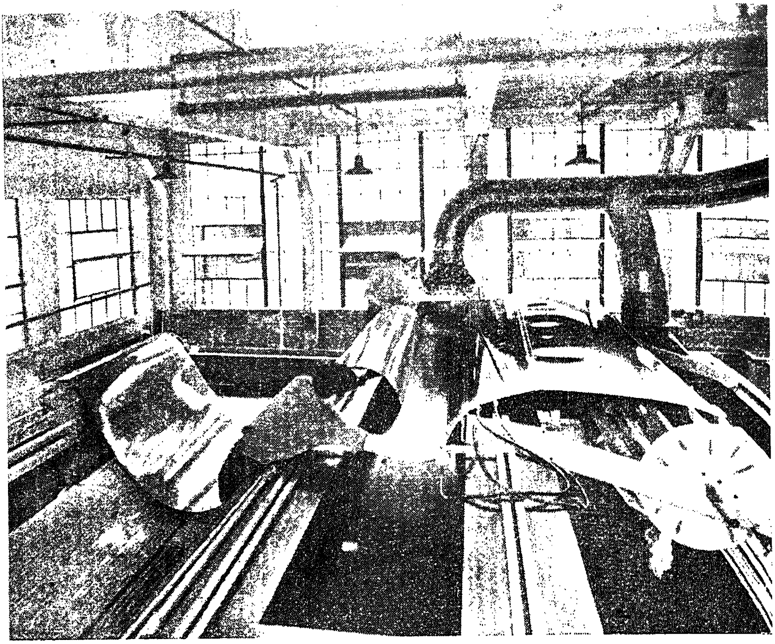

FIG. 114. A REEL OF ALCLAD ALUMINIUM ALLOY SHEET SHAPED FOR THE OUTER SKIN OF A SECTION OF THE 41-TON BOEING PAN-AMERICAN CLIPPER'S WING

The metal, seamed together by electric spot welding, is being anodized in the Finishing Shop of the Boeing Aircraft Company at Seattle

(*By courtesy of the Boeing Aircraft Company*)

Consolidated. The Consolidated Aircraft Corporation use a stressed skin wing structure which is based on the "centre-trunk" principle described on page 29.

The metal covering extends back behind the rear spar until it meets the false spar which carries the ailerons and flaps. This covering is supported inside by half-round stiffeners with outward turning flanges which are riveted to the skin. These are parallel with the rear spar, as will be seen in Fig. 115.

Behind the rear spar they are widely spaced, but over the more heavily stressed portions between the spars they are some 9 in. apart. Where the stiffeners run out due to the plan form taper of the wing a special pressing is put in to finish them off. The skin covering is put on in narrow strips running from front to back.

The rear spar runs straight across from tip to tip, but the front spar is swept back in accordance with the taper. There are no ribs in the ordinary sense of the word, but the wing is provided with diaphragms more closely spaced between the spars than behind. These are of flat sheet going right out to the wing surfaces and having flanges riveted thereto. The lateral stringers or stiffeners pass unbroken through notches cut in the rib flanges, but a second and continuous angle is provided running over the tops of the stiffeners.

The spars themselves are flat plate girders with double flange angles to the skin. The webs are divided into square panels with vertical stiffeners of the same form as is used to support the skin covering.

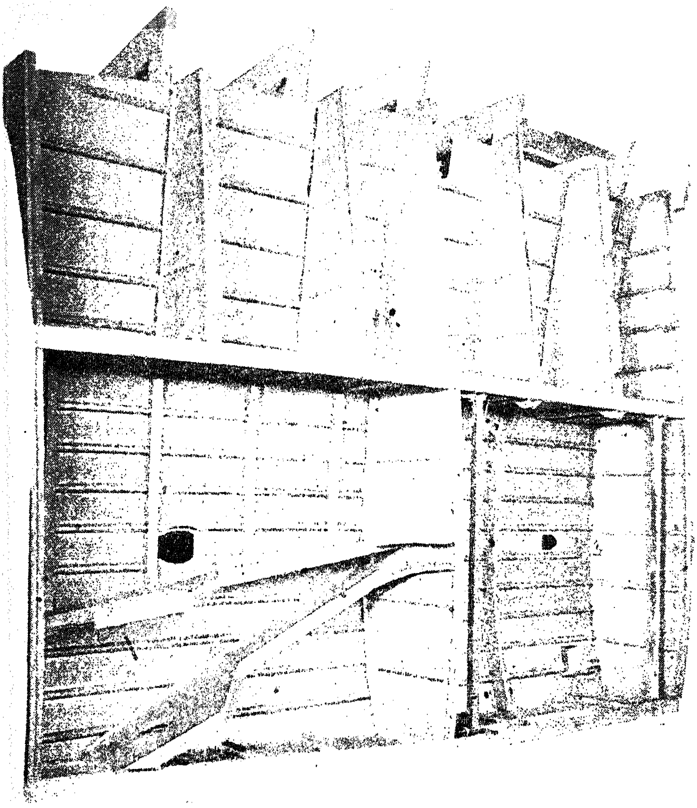

FIG. 115. CONSOLIDATED "PB2A" WING CONSTRUCTION
(*By courtesy of the Consolidated Aircraft Corporation*)

The wing shown in Fig. 115 is used on the PB2A Military Land Plane. A somewhat similar construction is used on the large Consolidated flying boats. In the PBY the centre section of the wing is made in one piece extending out to beyond the engine. That portion which lies between the spars is used as a fuel tank having a capacity of 1,750 U.S. gallons. One of these centre sections mounted on its handling bogey is shown in Fig. 116.

Curtiss-Wright. While fuselage design is now settling down to something like a standard monocoque construction, the structural design of wings is still in a state of flux. This view was expressed by Mr. T. P. Wright, Director of Engineering of the Curtiss-Wright Corporation.[1] Although his company appears to be producing only stressed skin wings of aluminium alloy, he makes a good case for the use of stainless steel in highly stressed wing spars. He suggests that an excellent wing might be built by using a single stainless steel spar from the leading edge back to 30 per cent of the chord, with a light rib-fabric cover construction aft thereof. This view is based on the

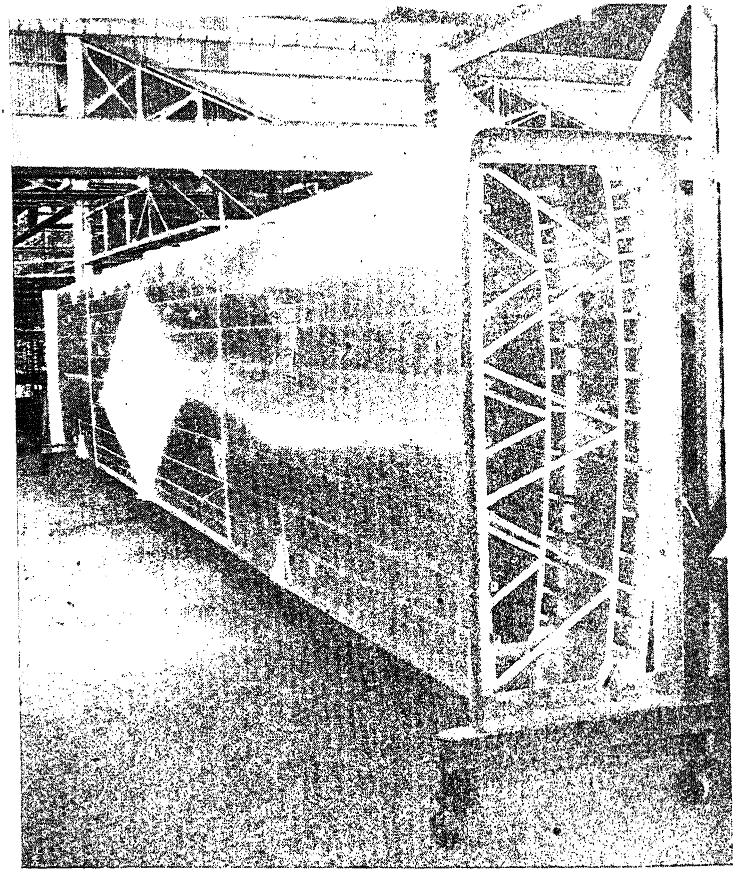

Fig. 116. Consolidated "PBY" Centre Section (Integral Fuel Tank)
(*Official U.S. Navy photograph*)

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[1] See *Journ. R.Ae.S.*, "American Methods of Aircraft Production," by T. P. Wright, F.I.Ae.S., F.R.Ae.S.

relatively low cost, the freedom from corrosion, the high strength, and the suitability of the material for electric spot welding.

In the meantime, however, a typical Curtiss-Wright wing structure is shown in Fig. 117.

This illustrates the wing root of the Curtiss-Wright 19 R. There are four main girders, having flat plate webs, which run out towards the tip of the wing. In between these are extruded bulb-angle section stringers, closely spaced on the flatter and more highly stressed parts of the upper and lower surfaces.

The wing profile is maintained by widely spaced inter-spar diaphragms of light alloy sheet, and these are riveted to the spars and covering. They are notched over the stringers.

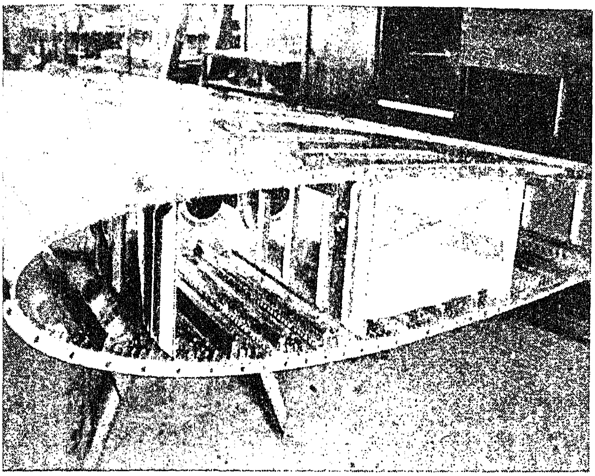

FIG. 117. CURTISS-WRIGHT "19R" WING ROOT
(By courtesy of Curtiss-Wright Corporation)

In order that full use shall be made of the potential strength of the covering, the loads which it is carrying are taken out through external boundary angles, very closely riveted to the covering and having a multiplicity of bolts for attachment to the centre section. If this were not done the loads carried in the skin would all have to be transferred to the spars before the root was reached and therefore the inner end of the skin would not be economically employed.

The under surface of the centre section of the Curtiss P 36–A is shown in Fig. 118.

The spaces between the spars are well filled with fuel tanks and outside these are the cavities into which the wheels retract. Although the under surface is thus broken up, continuity is preserved in the leading and trailing edges and in the upper surface, the latter being supported by very closely spaced stringers. The strong angle joints on the centre line will be noticed.

In the Curtiss-Wright factory, the units are made up in a number of sub-assemblies, leaving only a relatively small amount of work to be

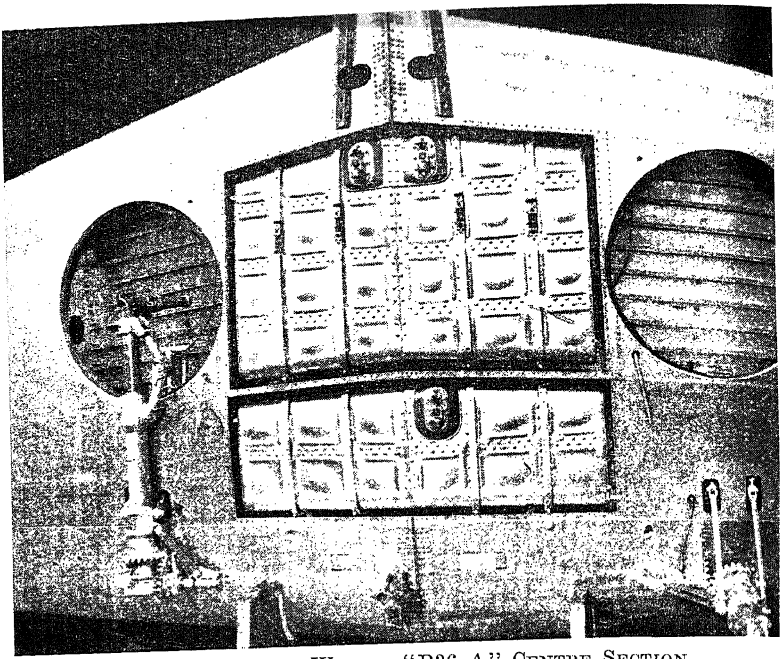

Fig. 118. Curtiss-Wright "P36–A" Centre Section
(*By courtesy of Curtiss-Wright Corporation*)

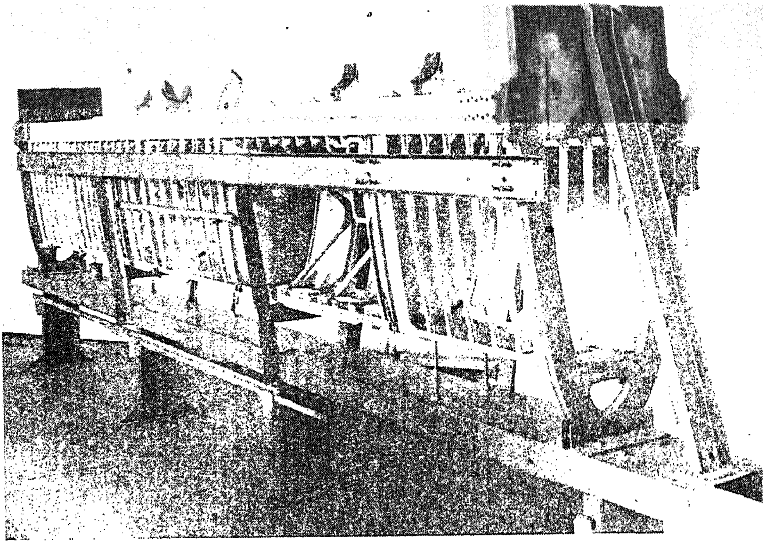

Fig. 119. Curtiss-Wright "Y1A–18" Leading Edge
(*By courtesy of Curtiss-Wright Corporation*)

done on the master assembly jig. This allows more labour to be employed without overcrowding, and it is shown in the Y1A–18 fighter aircraft, in which a single spar construction with a torsion resisting leading edge was used (see Fig. 119).

Douglas. The wing construction of the Douglas D.C.2 is of a type which has become extremely popular in America. There are three spars with flat plate webs having extruded bulb-angle sections riveted to their top and bottom edges. To the flanges of these angles is riveted the flat skin which covers the whole wing on both surfaces.

It has been usual to regard such a skin as being capable only of taking the drag and torsion loads since it begins to buckle under any considerable stress. This is particularly true of the upper surface which forms the compression side of the girder under normal air loads. Even if stiffened with angle or channel sections running laterally along the inside, the tendency of the skin to buckle is such that it will tear out the rivets attaching it to the stiffeners. In the Douglas an inner skin is fitted having closely spaced corrugations running from tip to tip. This forms a wide belt from near the leading edge across the top of the section to the rearmost of the three spars and it is securely riveted to the outer smooth surface. It forms in effect a series of close stiffeners to the surface and holds it up to a much higher stress, both in bending and in shear.

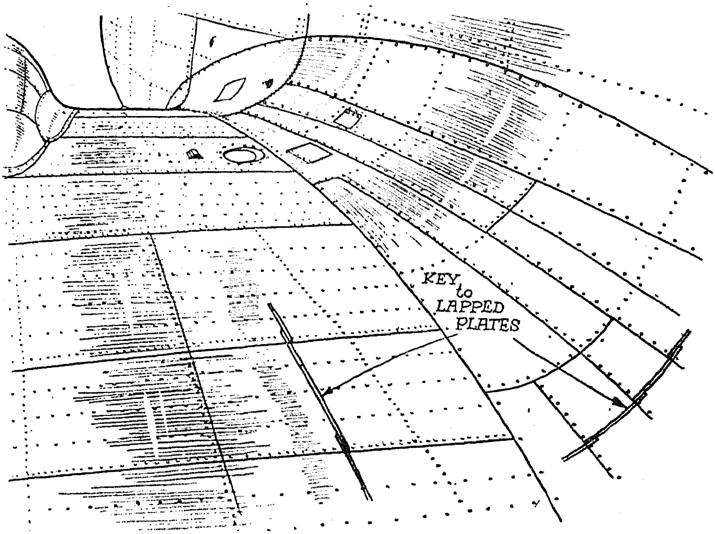

FIG. 120. DOUGLAS D.C.2. WING ROOT
(*By courtesy of "The Aeroplane"*)

The lower surface which is normally under tension and shear has much less tendency to buckle. It is stiffened by extruded bulb angles riveted inside between the spars and parallel to them.

The method of attaching the outer surface skin is shown in Fig. 120, from which it will be seen that the panels of plating are lapped over each other, starting from the trailing edge and working forward. The large root fillets are built up of narrow curved strips pressed to on lead-zinc formers.

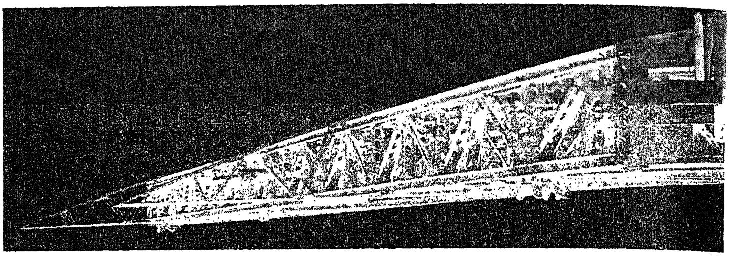

FIG. 121. GLENN L. MARTIN MONOPLANE WING STRUCTURE
(By courtesy of the Glenn L. Martin Co.)

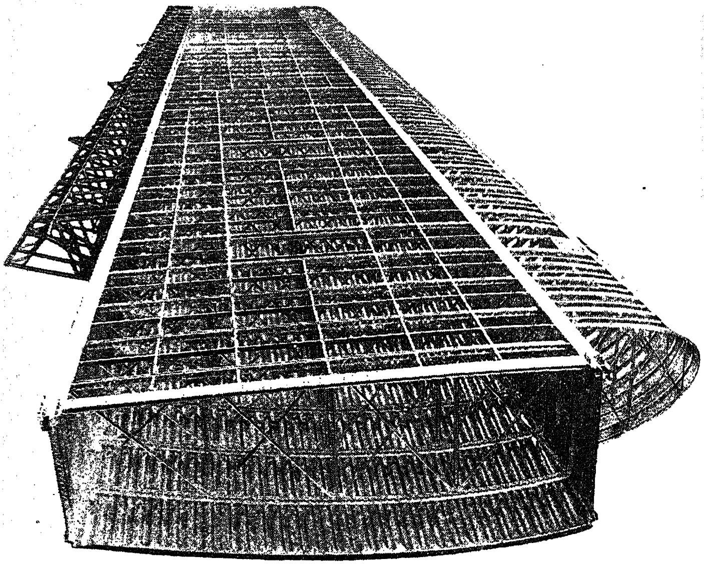

FIG. 122. GLENN L. MARTIN "CHINA CLIPPER" WING CONSTRUCTION
(By courtesy of the Glenn L. Martin Co.)

The cross section of the wing is preserved by the three spars and by fore-and-aft diaphragms having large lightening holes.

Glenn L. Martin. The spar (see Fig. 121) is a very typical example of

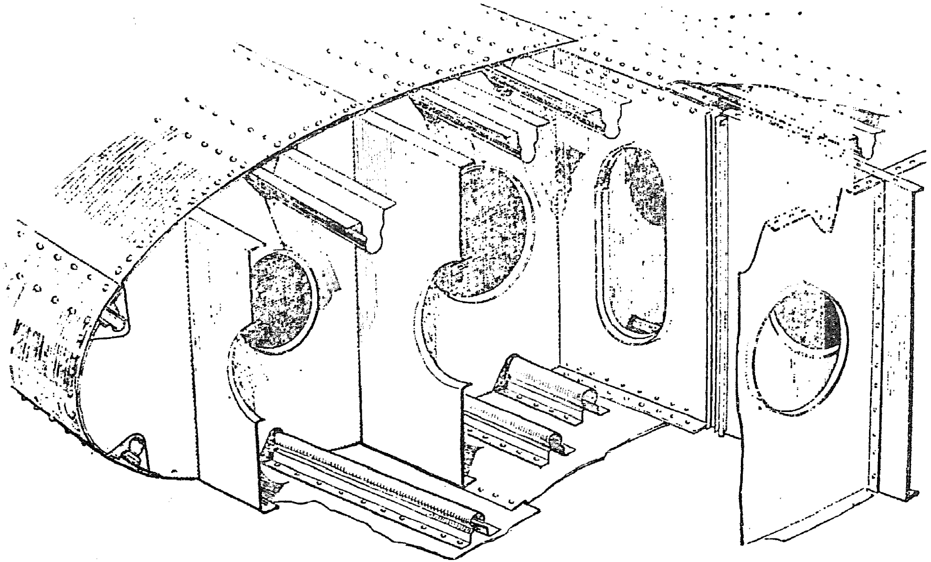

FIG. 123. NORTHROP WING STRUCTURE
(*By courtesy of "Flight"*)

the lattice girder construction which is becoming popular for large thick section and tapered monoplane wings. The material used by this firm has, in the past, been the aluminium alloy 17S, but they are now turning over to 24S, which has similar working characteristics to duralumin, but slightly higher physical properties. The channel sections are all fabricated from sheet in the aircraft factory and extruded sections are little used. In this kind of spar, the loads are all resolved into direct tensile or compressive end loads in the various units as in a roof truss or similar braced frame. The continuity of the flanges, however, reduces the free deflection length in each short bay and the diagonal and vertical bracings between the flanges can scarcely be considered as pin-jointed, since their attachments consist of large gusset plates well riveted to each unit. The joint fittings are of welded chrome molybdenum steel, which are heat treated after welding.

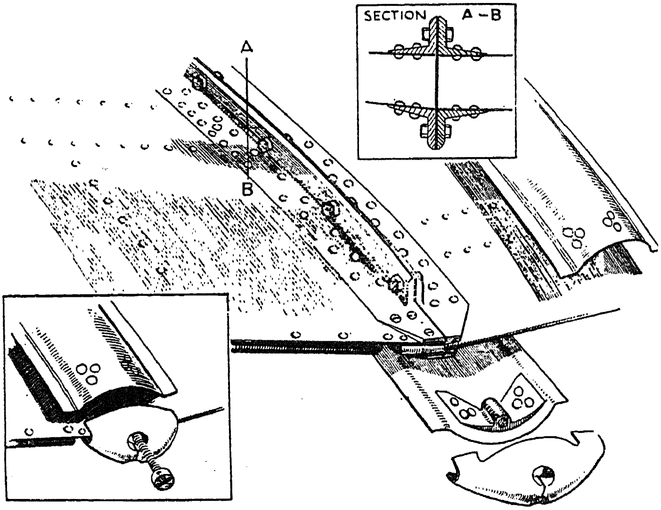

FIG. 124. NORTHROP WING ROOT
(By courtesy of "Flight")

Fig. 122 shows the internal construction of the wing of the China Clipper flying boat. The bottom skin is removed to show details. The wing is of the box type. Corrugated sheet is riveted to the inside of the upper skin to carry compression. The front and rear spars have thin sheet webs and the bottom skin is flat, taking tensile loads. As most of the bending is carried in the top and bottom surfaces, the spar flanges are small. The spar webs are shear girders and have closely spaced stiffeners to reduce buckling. This wing is very stiff in torsion, the whole box section being in shear. The rib booms are channel sections separated in each case by three tubes, the rectangular panels so formed being cross braced. Intermediate transverse and longitudinal channels stiffen the flat lower surface. In the leading edge there are closely spaced girder ribs but no stringers inside the metal skin. If the wing structure is compared with the hull of this boat (see Fig. 283), it will be appreciated that the same structural principles have been used in each case. A similar construction was used in the Martin B-10 twin engine bomber. The wing of this machine with an area of 678 sq. ft. and a loading of 23 lb. per sq. ft. had a total weight of 2,020 lb. This is equivalent to 3 lb. per sq. ft. wing weight and 13 per cent of the all-up weight of the machine.

Northrop. An original but entirely logical form of monoplane wing construction was developed for the Northrop 2E bomber. In accordance with the principle that a "stressed skin" wing must be lightly stressed. there were no main members into which the loads could be concentrated, The method can be described as "multicellular." A number of flat webs extended from tip to tip, the deeper ones having extruded angles riveted to the top and bottom edges, and the shallower ones being flanged over. To these and to the flanged rib plates was riveted the flat skin, which was further stiffened by "omega" sections inside, parallel to the spar members. (See Fig. 123.)

The wing was made in three portions, the outer ones being attached to a centre section on to which the fuselage is built. Since the loads are distributed as widely as possible in the structure, the joints between the outer and centre portions were designed to accommodate this fact. Around the ends of the abutting sections are flanges made from heavy extruded angles riveted on to the skin. When the wings were assembled a flat plate, cut to the wing profile, was inserted between the flanges and the whole bolted through with closely spaced bolts and nuts. The joint was afterwards covered with a V-section strap, drawn tight by bolts at each end. (See Fig. 124.)

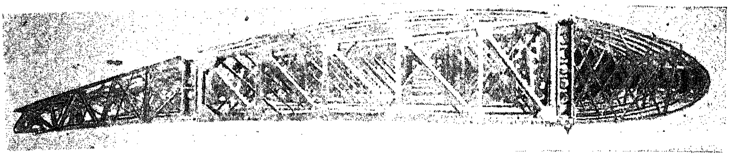

FIG. 125. SIKORSKY S.40—MAIN PLANE STRUCTURE
(By courtesy of the Sikorsky Aviation Corporation)

The structure of this machine appears to be very light. With a wing loading of over 20 lb. per sq. ft., the bare weight is 3,750 lb. for an all-up weight of 7,500 lb. This is evidently due to careful design and the multicellular construction lends itself to light members. Possible objections to it for a commercial aeroplane are that the division of the wing into small sections prevents the interior being used to stow petrol tanks, or the undercarriage if retractable. Concentrated loads from the undercarriage or from wing engine mountings would need special study and for the latter it would probably be necessary to use monocoque mountings of the kind described on page 308.

Sikorsky. The Sikorsky S.40 amphibian flying boat was a large machine with a parasol monoplane wing supported at numerous points by an external braced structure underneath. The wing construction was orthodox in lay-out. There were two deep lattice girder spars of the type already described above. The material was duralumin but the sections used for the flanges were extruded channels, whilst the bracings were pressed and connected to the flanges by riveted gusset plates. The drag struts, one of which can be seen in Fig. 125, were of similar construction. An extruded channel ran between the top flanges of the front and rear spars and a similar one between the lower flanges. These were braced with pressed channel members, also attached with riveted gussets. The ribs were built up from extruded T-sections for the cappings and with extruded channels for the bracing. A false spar carried the aileron hinges, and was cantilevered on brackets which continued the drag struts behind the rear spar. The covering was of fabric and the wing was braced against drag and anti-drag loads with crossed high-tensile steel wires in the planes of both top and bottom flanges.

The monoplane wing of the later S 42-A type is metal-clad as far back as the rear spar. Behind this to the false spar, which carries the flaps and ailerons, is fabric covered. The construction is otherwise somewhat similar to that of the S.40. The spars are warren girders of extruded sections, the flanges being of semi-circular section with turned-in lips and the bracings of extruded *H* sections with lightening holes (see Fig. 126). The bracings are attached to the flanges with riveted gusset plates on each side.

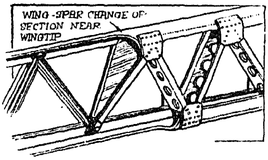

FIG. 126

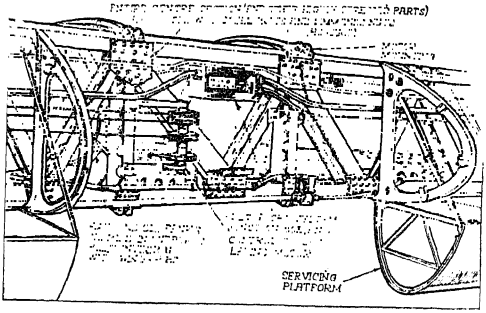

FIG. 127

(*By courtesy of "The Aeroplane"*)

FIGS. 126–7. SIKORSKY "S42–A" WING DETAILS

Highly stressed joints are bolted, using elastic stop-nuts. The spars are connected to each other by heavy drag ribs. Throughout the centre section of the wing, behind the engines, these drag ribs divide the space into rectangular compartments, which contain the cylindrical fuel tanks (see Fig. 127).

The skin, like the hull which is described on page 242, is flush riveted all over. A special form of rivet is used with the head recessed underneath. The rivet is put in from inside and the skin dimpled down into this recess as the head is pressed flush outside.

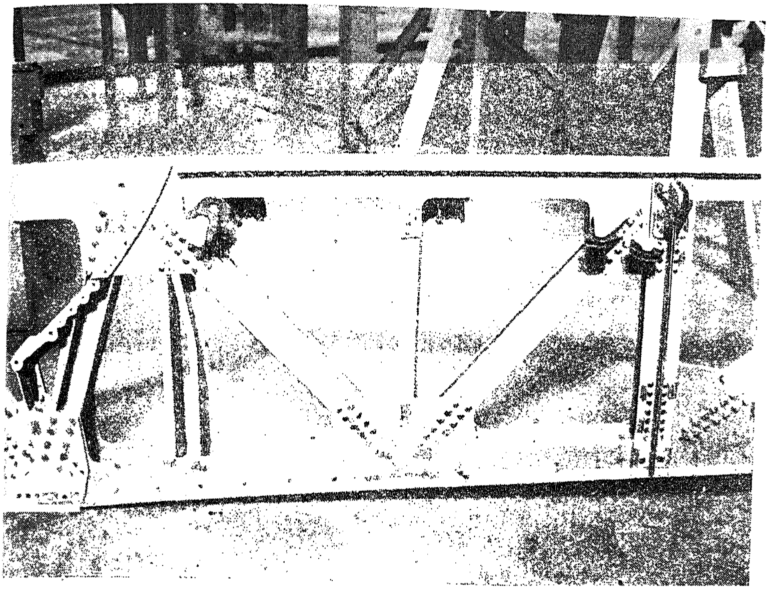

FIG. 128. VULTEE "V-11" SPAR
(*By courtesy of Vultee Aircraft*)

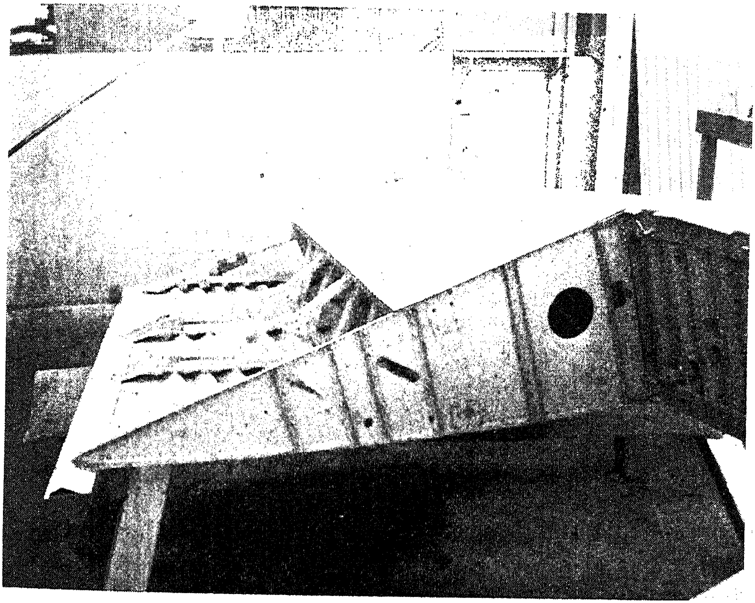

FIG. 129. VULTEE "V-11" TRAILING EDGE
(*By courtesy of Vultee Aircraft*)

Vultee. The main plane construction of the Vultee V-11 series of military aircraft is shown in Figs. 128 to 134.

The centre section consists of a framework formed by the front and rear spars combined with fore-and-aft ribs and bulkheads. The front spar (see Fig. 128) is of open truss construction with continuous aluminium alloy extruded flanges. Both diagonal and vertical members

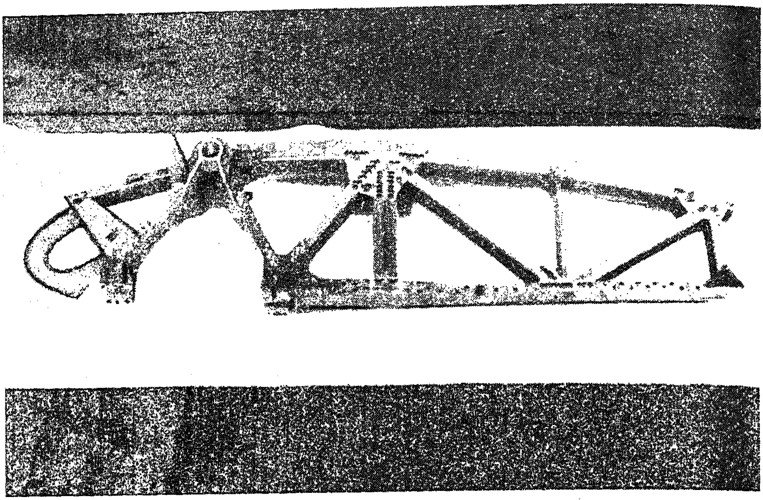

Fig. 130. Vultee "V-11" Centre Section Rib and Undercarriage Attachment

(*By courtesy of Vultee Aircraft*)

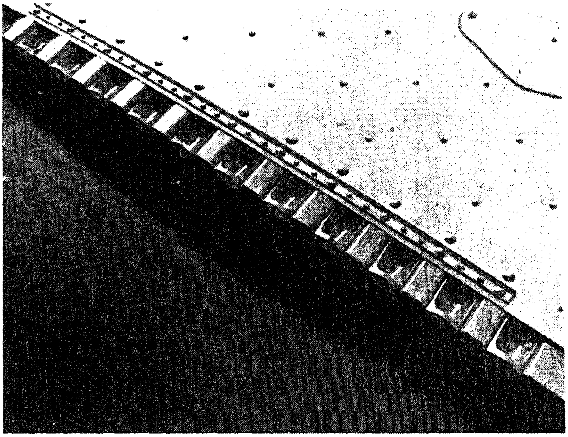

Fig. 131. Vultee "V-11"—Joint in Skin

(*By courtesy of Vultee Aircraft*)

are also extruded aluminium alloy sections. The flange members are extruded with deep webs which are machined back leaving standing the gussets to which are attached the bracing members. The rear spar, shown in Fig. 129, is built up of smaller extruded flanges, but the web consists of vertically corrugated sheet. This illustration also shows the trailing edge ribs.

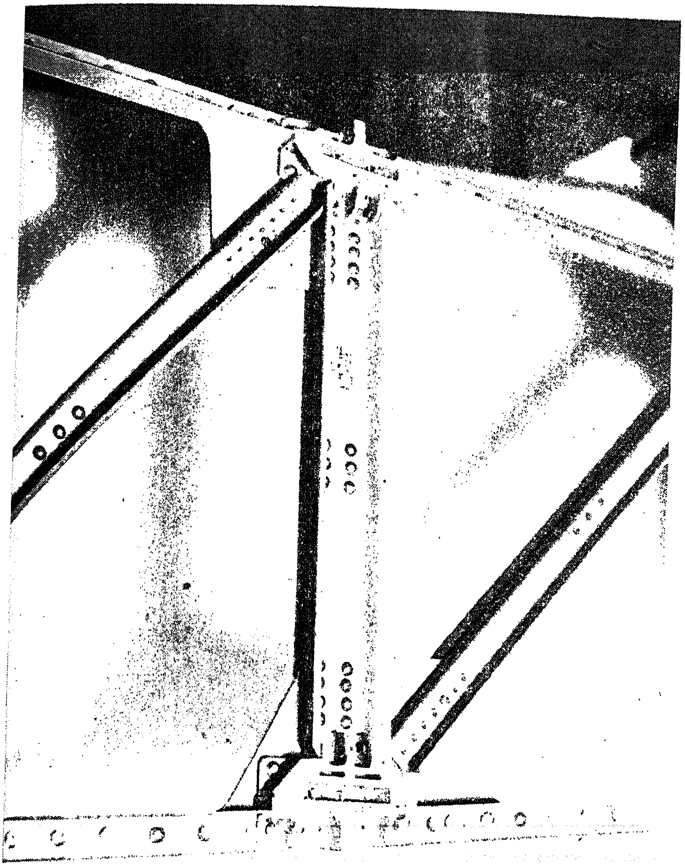

FIG. 132. VULTEE "V-11" LEADING EDGE ATTACHMENTS ON SPAR

(*By courtesy of Vultee Aircraft*)

The top and bottom surfaces between the front and rear spars are covered with sheet corrugated spanwise to form a rectangular structure which is torsionally rigid. At the outboard end of the centre section is a strong rib which carries the undercarriage, the attachment fittings for which can be seen in Fig. 130. The upper fitting houses the worm which actuates the undercarriage retraction (see p. 284).

The construction of the outer section is similar to that of the centre

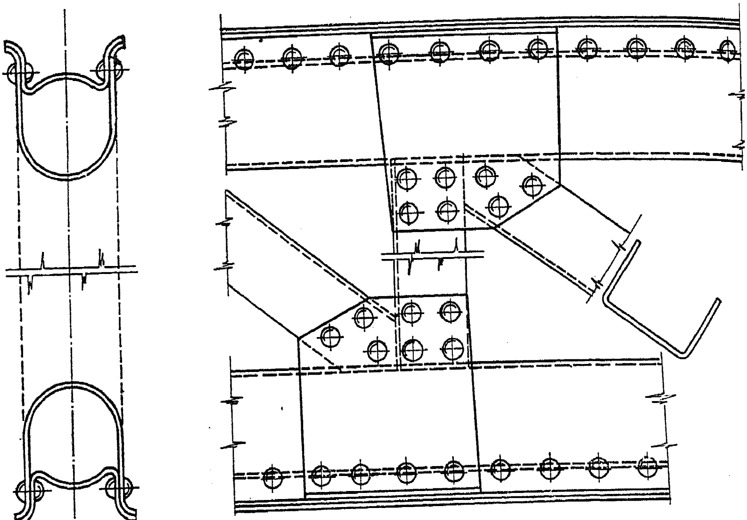

FIG. 135. AVIA, TYPE 51: SPAR

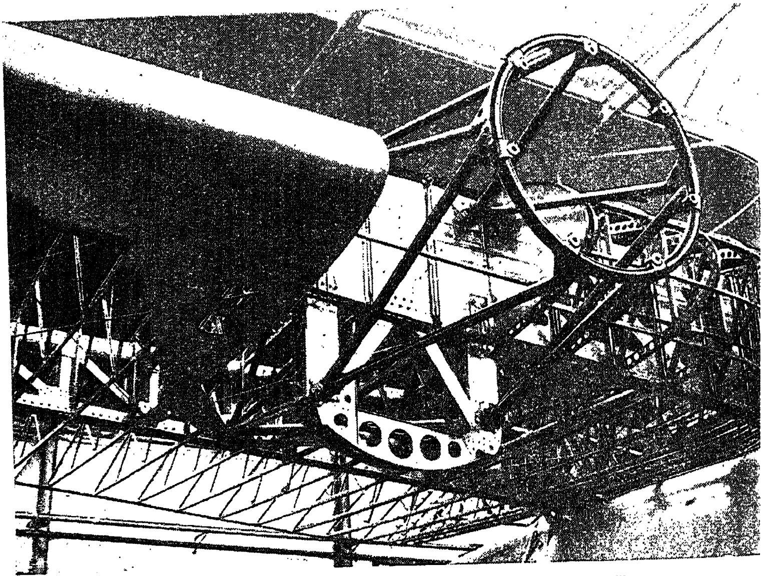

FIG. 136. AVIA, TYPE 51: FABRIC-COVERED WING

(By courtesy of Avia)

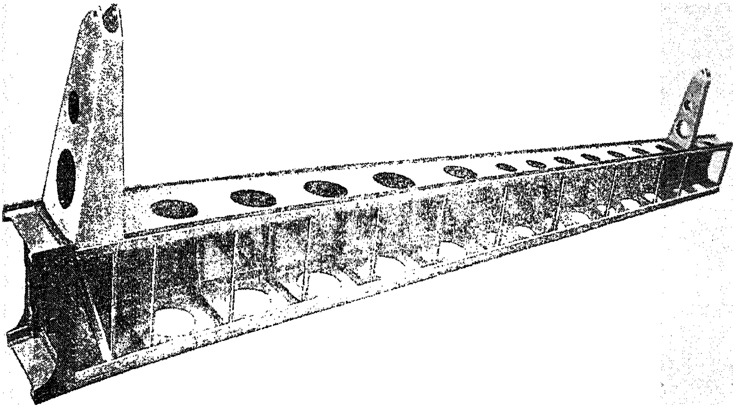

FIG. 137. LETOV S32 SPAR CONSTRUCTION
(*By courtesy of Letov*)

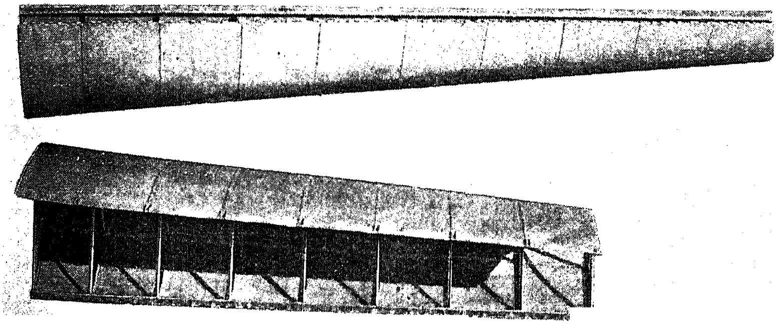

FIG. 138. LETOV S32 LEADING AND TRAILING EDGES
(*By courtesy of Letov*)

with outstanding lips riveted together. Between the spars the rib booms are braced with similar tubes in N-girder fashion, whilst in the trailing edge warren girder bracing is used. No stringers are used to tie the ribs together under the fabric.

The wing is built in one piece from tip to tip and mounted on the top of the fuselage (see Fig. 202) by four fittings, one each side at the front and rear spars. Conical bolts are used for making the attachment.

Letov. The cantilever wing of the Letov S32 transport is built on the Rohrbach system as described on page 148. The foundation of the wing is a wide box spar at the deepest section. The front and rear walls are lightened with large circular flanged holes. These walls and the upper and lower surfaces of the box are stiffened with cross frames inside. Fig. 137 shows this spar, with the lower surface left off. The backward extensions to carry the aileron hinges may be clearly seen.

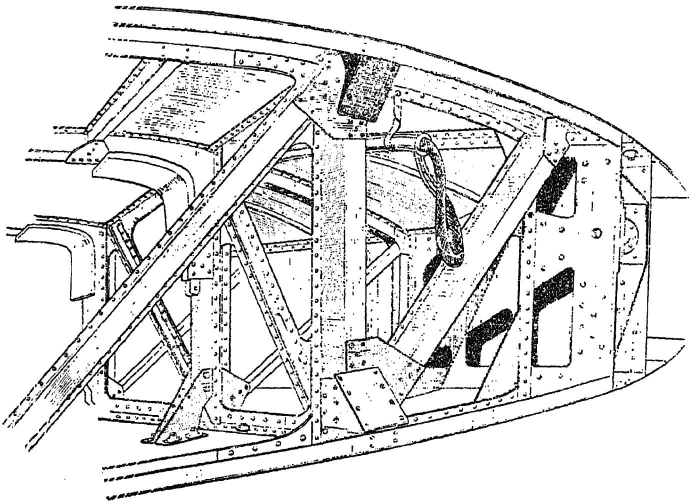

FIG. 139. FARMAN WING CONSTRUCTION
(*By courtesy of L'Aéronautique*)

The wing is completed by adding metal covered leading and trailing edges. The lengths of leading edge (Fig. 138) are attached by long hinges at the top and bottom of the front wall of the spar.

FRANCE (STATE FACTORIES). **S.N.C.A. du Centre.** The S.N.C.A. du Centre combines the aircraft factories previously owned by Farman and Hanriot. The wing structure of the Farman 223, now known as the C.223, will first be described.

The wing structure is composed of two half wings attached directly to the fuselage sides. Each half wing has a principal central spar supported by a single strut, the assembly of the spar and strut forming a very stiff girder stressed to carry all the vertical loads. There is, in addition, a front spar forming the leading edge, and a rear spar consisting of two omega sections. The three spars together carry a framework of ribs and stringers to which are riveted the covering. Large fuel tanks are built into the centre section. The attachment of each half wing to the fuselage is made by four joints situated respectively in line with the front and rear spars and the two flanges of the centre spar (Fig. 139).

The Hanriot N.C. 510 is a small twin-engine reconnaissance machine. The wing is in the high position and has "V" bracing struts running from the inner side of the engine mounting to the bottom longeron of the fuselage. While this external bracing causes additional aerodynamic drag it is compensated by the weight which is saved in the most heavily loaded portion of the wing structure. The undercarriage is fixed and mounted directly under the engine with which it is built integrally. Some details of these may be seen in Fig. 140.

The two spars are built as plate girders having single webs and extruded flanges. Each flange is in a single piece like a flat channel having a centre double extension into which the web is inserted. At points of high stress additional laminations of flat plate are riveted on to the flange members. The web is supported at close intervals by channel sections backing on to the web and riveted thereto. The way in which the undercarriage structure is incorporated with the engine mounting will be seen in the illustration.

The whole arrangement is extremely efficient structurally and should give great rigidity combined with light weight. The outer sections of the wing join on to the centre section at the outer sides of the engine mounting, and heavy fish plates extend outwards from the centre section of the spar flanges to pick up the outer spars.

Another view of the same structure illustrating the "V" struts down to the fuselage is seen in Fig. 141.

It will be seen that where the spar load is reduced at the junction of the external struts, the spar itself tapers to a single attachment on the fuselage.

S.N.C.A. du Midi. The S.N.C.A. du Midi incorporates some of the interests of the late Dewoitine and Lioré et Olivier factories. The Dewoitine Company had specialized for many years on single spar wings (Fig. 142) for both high and low wing monoplanes.

In the D.332, the spar was placed at one-third of the chord of the section. It was made up of two flanges with a double web of duralumin sheet, lightened with triangular holes to form a trellis. The flanges decreased in thickness from the centre to the tip to maintain an equal stress. The vertical slats of the web corresponded to the rib positions and were braced across with diaphragms, front to back, the full depth of the spar. The oblique slats, which were normally in tension were reinforced on the outside with omega sections riveted on.

For the purposes of transport, the wing was built in five parts, and the lengths of spar were connected together with high-tensile steel hinges on the top and bottom flanges.

The spar was designed to carry only bending load, and since local buckling was, to a large extent, prevented, the material practically developed its full strength.

Torsional loads were taken by the leading edge. This was stiffened by channel members, both longitudinally and laterally, and covered with thin duralumin sheet. It was attached to the spar flanges, top and bottom, by two long hinges, through which runs a high-tensile steel wire of 2 mm. diameter. The leading edge was thus detachable in sections corresponding to those of the spar and allowed easy assembly and maintenance.

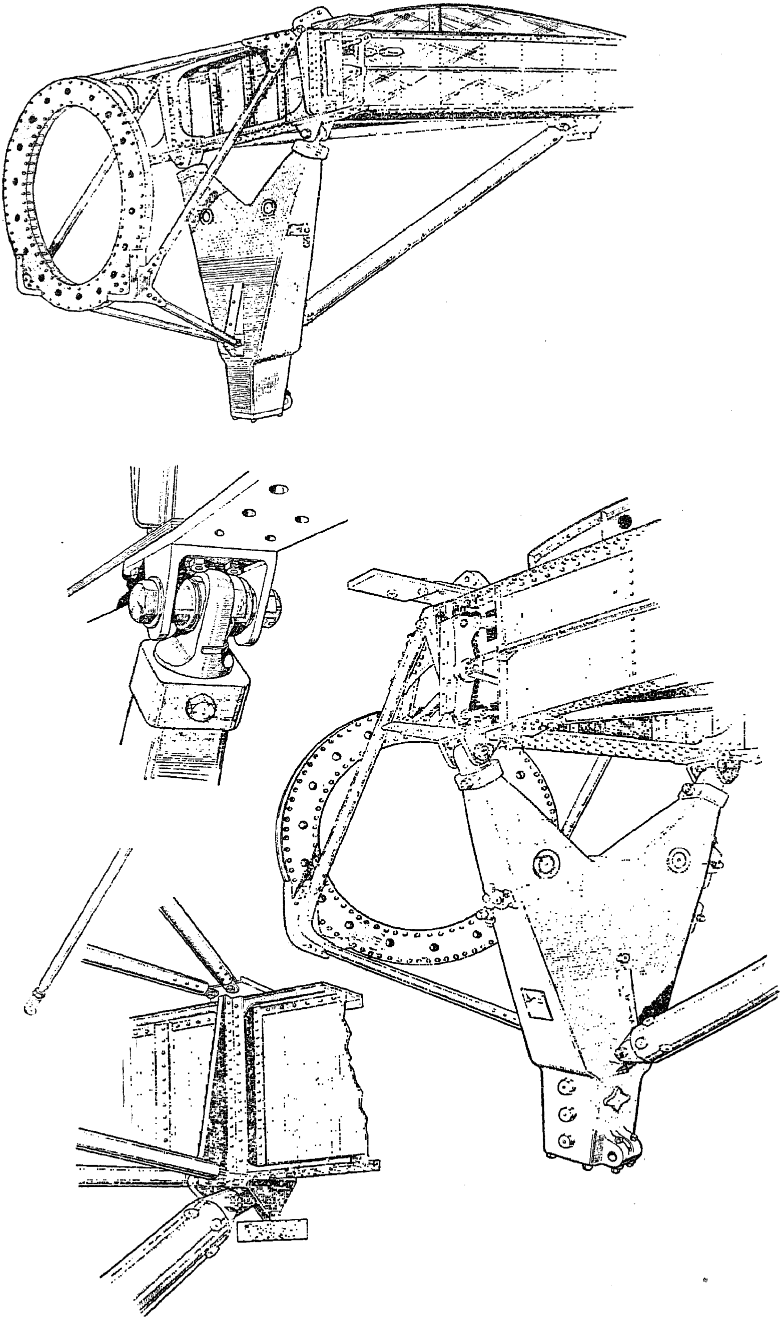

Fig. 140. Hanriot “N.C.510” Wing Details

(By courtesy of L'Aéronautique)

Ribs of normal tubular design ran backwards from the spar to the aileron false-spar. This portion of the wing was also covered with thin duralumin sheet in panels riveted on.

The weight ratios of Dewoitine commercial machines are remarkably high. The D.332 carried more than its own weight in disposable load, which points to an extremely light structure. (For the assembly of this wing on the fuselage, see Fig. 203.)

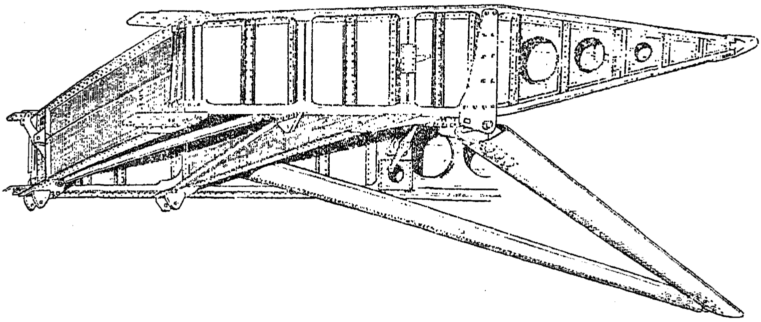

Fig. 141. Hanriot "N.C.510" Centre Section

(*By courtesy of L'Aéronautique*)

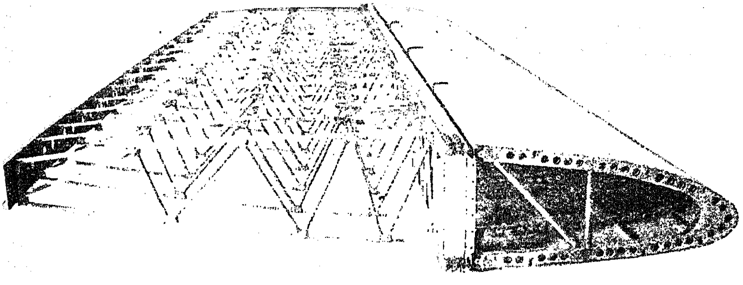

Fig. 142. Dewoitine Single-spar Wing

(*By courtesy of the Société Aéronautique Française*)

This type of structure has been developed by S.N.C.A. du Midi, and very great savings in workmanship, time, and labour charges have been effected.

There are two types of wing structure used on Dewoitine fighter aircraft, one being similar to that of the D.332, while the other one is the D.520. The older type of ribs required 1,360 hours per machine, while the new ones require only 60 hours.

Similar savings have been made in the spar construction, which in the earlier aircraft was a box section, whereas in the new one it is of the single web type with extruded flanges on each side. The new type requires only 7,000 hours per machine, whilst the older one needed 14,000;

the economy in time resulting from the new methods is, therefore, 50 per cent.

The design of units for real production making great use of pressings, of spot welding, and of mechanical riveting has made this possible. The saving has been made entirely in the unit construction, since it was found impossible to make any economy in the main assembly work, and the extent of the improvement will have been further realized if one allows for the fact that the newer aircraft had the additional complications of a retractable undercarriage and a variable pitch airscrew.

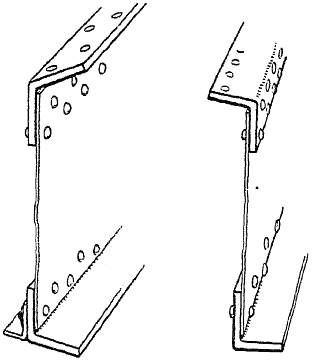

FIG. 143. POTEZ "63" SPARS
(*By courtesy of "Aircraft Production"*)

S.N.C.A. du Nord. The S.N.C.A. du Nord combines the factories of the late C.A.M.S. and Potez companies.

One of their most important products is the Potez 63 produced in large quantities for the French Armée de l'Air. The details and production methods for this aircraft have been very completely described in the English technical press.[1]

It is a twin-engine three-seat fighter-bomber monoplane of high performance. The structure is entirely aluminium alloy with a stressed skin covering of vedal, which is a material similar to the more familiar alclad. The wing has two spars and is built in three sections; the centre section being rectangular, and the outer sections tapered. The wing tips are detachable and bolted on to the spar ends.

The centre section carries the fuselage, engine, fuel and oil tanks, and the retractable undercarriage. The top and bottom flanges of each spar consist of tapered obtuse angle aluminium alloy sections. These are made up in 16 ft. lengths and joined with fish plates at two-thirds of the span out from the centre section.

When received into the factory the flanges are straight symmetrical sections, but after being straightened they are set to the correct obtuse angle to suit the wing profile. In order to taper them to give an even distribution of stress, they are set up in a special milling machine which has a saddle type carriage embodying the cutters. The cutters revolve at 1,600 r.p.m. and transverse up to 32 in. per minute, depending on the cut. When the spar flanges have been milled they are then profiled. A pattern is attached to each face in turn and passed across a high-speed vertical cutter which is similar to a wood spindling machine. On completion of the profiling operation the rough edges are removed and the drilling of rivet and bolt holes begun. Drilling jigs are attached to the angles and the equipment is such that 150 holes per hour can be drilled. The drill is of the self-centring type and the chuck is spring loaded so that the load of the drill can be controlled. The spar beam remains in the jig during the drilling operation and for the subsequent tapping of those holes which require it. Small pneumatic hand drills are used for this tapping and for the countersinking of the tapped holes.

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[1] "Aircraft Production," October–November, 1939.

The spar webs are of aluminium alloy sheet and are stiffened vertically with angles which are spaced about 5 in. apart at the root increasing gradually to 10 in. apart at the tip. Where extra strength is required the stiffeners are duplicated. For assembly the flanges and webs of the spar are placed in jigs and the flanges are used as templates for drilling the webs. The free edges of the front spar flanges point aft and the web is riveted to the inside or rear vertical face. The final form of the front spar is, therefore, a channel section. The rear spar, however, is of "Z" form with the top free edge pointing forwards and the bottom one aft. The spars are shown in Fig. 143.

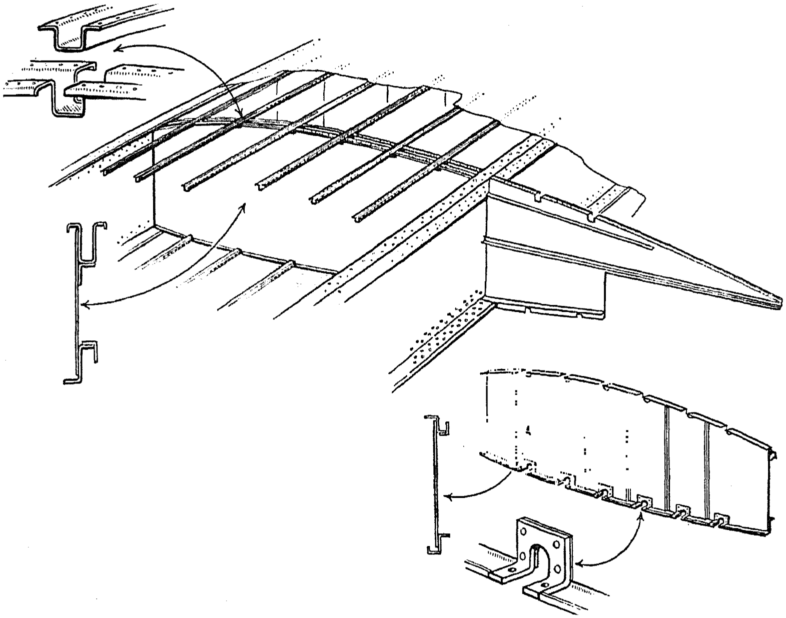


FIG. 144. POTEZ "63" WING CONSTRUCTION
(*By courtesy of "Aircraft Production"*)

There are only seven main ribs in each outer section, four of which are made in two parts extending from the front spar to the trailing edge, the other three from the front spar to the aileron joints only. The ribs consist of flat sheet webs with pressed angle flanges. The flat web is stiffened by vertical angles which are spot welded by the Sciaky process (see page 377).

Where the ribs are notched to allow the transverse skin stiffeners to pass through, the notches are stiffened by means of small pressed angles as shown in Fig. 144.

The transverse stiffeners are of top hat section while in between the ribs there are intermediate fore-and-aft stiffeners.

The wing tips are made up separately and attached to the ends of the spars. The navigation lights are faired into the leading edge of these tips (see Fig. 145).

S.N.C.A. de l'Ouest. The S.N.C.A. de l'Ouest embodies the organization of the Loire and Nieuport companies, and is now principally engaged in the production of small single and twin engine military aircraft.

The wing structure of the Loire et Nieuport 161 is shown upside-down in Fig. 146. The lower skin is removed so that the inner structure may be seen.

The upper sketch shows the root section of the wing where it joins on the fuselage side and the cavity into which the undercarriage retracts. The main structural member is a single box spar built up of flat aluminium alloy sheet with external corner pieces. There is apparently a rear spar, but it will be seen that this is attached to the fuselage by a single fitting, and cannot, therefore, take any bending loads. It must be assumed that its only use is to assist in the transmission of torsional and drag loads. The end fittings which attach the main spar to the fuselage are designed with three tongues so as to put the main attachment bolts into multi-shear. Flat plate ribs at a fairly wide spacing support the skin covering and extend back to the rear spar. The square panels of skin so formed are supported by longitudinal and transverse stiffeners of omega section.

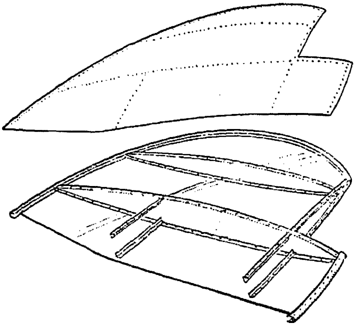


FIG. 145. POTEZ "63" WING TIP

(*By courtesy of "Aircraft Production"*)

S.N.C.A. du Sud-Est. Certain of the factories of the Lioré et Olivier and the Romana companies are now incorporated in the S.N.C.A. du Sud-Est, of which Monsieur Mercier, well known for his engine cowling research, is Chief Engineer.

They are principally engaged in the construction of large multi-engined land planes and flying boats.

The wing construction of the LeO45 bomber makes great use of corrugated sheet for stiffening. This practice is more common in Great Britain and the U.S.A. than in France. Various details are shown in Fig. 147.

The wing is built in four parts, two centre sections, one on each side of the fuselage, carrying the engine nacelles and the retractable under-carriages; and two outer sections on which are mounted the ailerons.

The centre sections each comprise two spars having steel flanges and duralumin webs (between which are mounted the fuel tanks, two on each side), a removable leading edge and a trailing edge built in with the rear spar carrying the flaps. The spars are joined together by corrugated sheet, the corrugations running fore-and-aft covered with smooth sheet.

The outer sections are of box construction, the flanges consisting of panels of corrugated sheet (corrugations parallel with the span) covered with flat sheet. The leading and trailing edges are removable.

The wing root attachments are heavy fittings which key on to corresponding fuselage points after the manner of a mortice joint. The corresponding fuselage fittings appear in Fig. 209. The attachments for the removable leading edge are also clearly shown.

The SE 200 built by the S.N.C.A. du Sud-Est is a large transatlantic flying boat of nearly 170 ft. span. The wing structure is built integral with the upper part of the hull and consists of a centre trunk of which the upper and lower surfaces are in corrugated sheet, and the vertical webs in stiffened flat sheet. Interior ribs are lattice structures of square tubes.

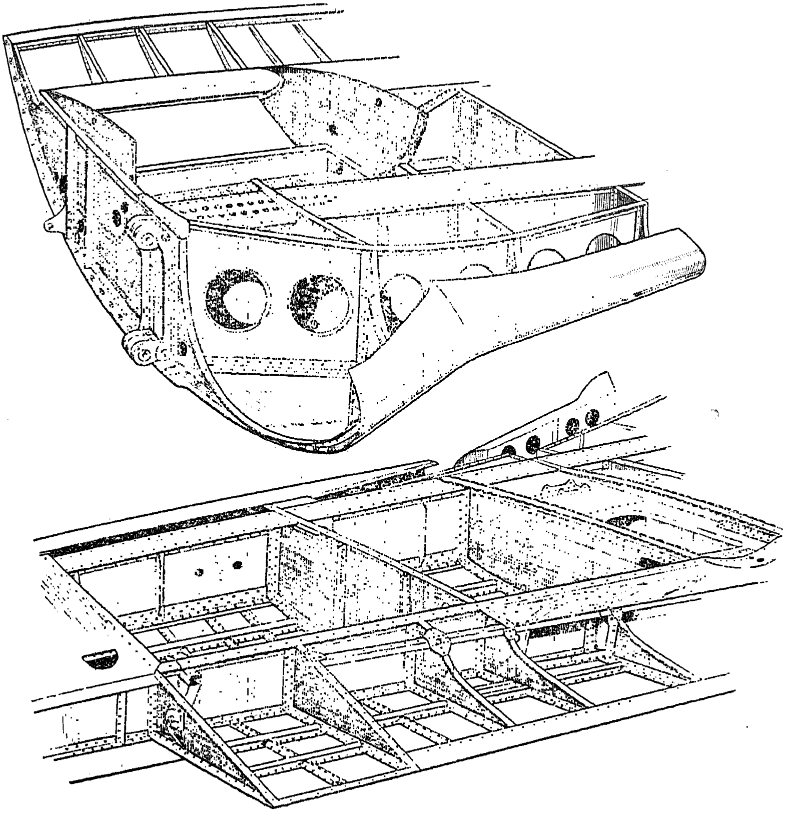


FIG. 146. LOIRE ET NIEUPORT "161" WING CONSTRUCTION

(*By courtesy of L'Aéronautique*)

In the centre trunk, ribs of flat sheet divide the trunk into compartments forming fuel tanks, which are situated on each side of the hull. That portion of the centre trunk which passes across the hull is used as a baggage compartment. As in the LeO 45 the leading edge is detachable, and in the neighbourhood of each engine it forms hinged platforms for engine maintenance work. The trailing edge, like the rest of the wing structure, is covered with vedal sheet, a material similar to alclad.

S.N.C.A. du Sud-Ouest. The S.N.C.A. du Sud-Ouest combines certain of the interests of Bleriot, Bloch, Breguet, and Lioré et Olivier.

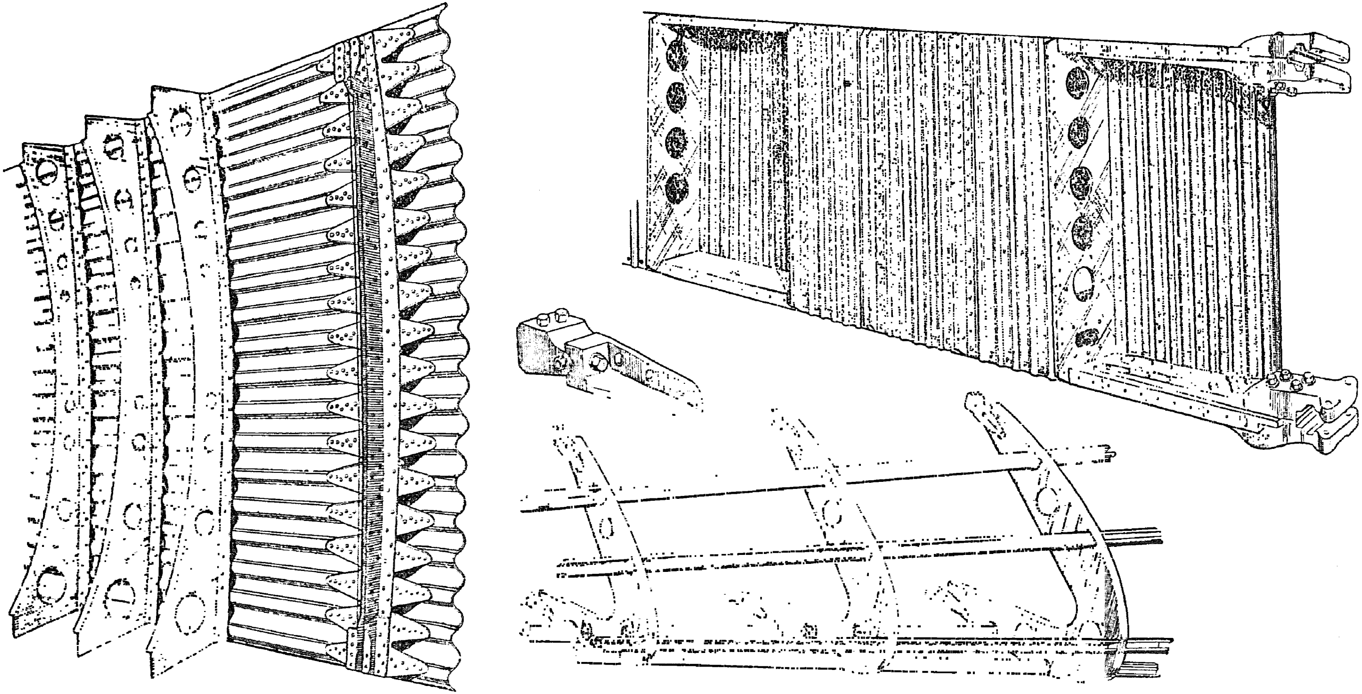
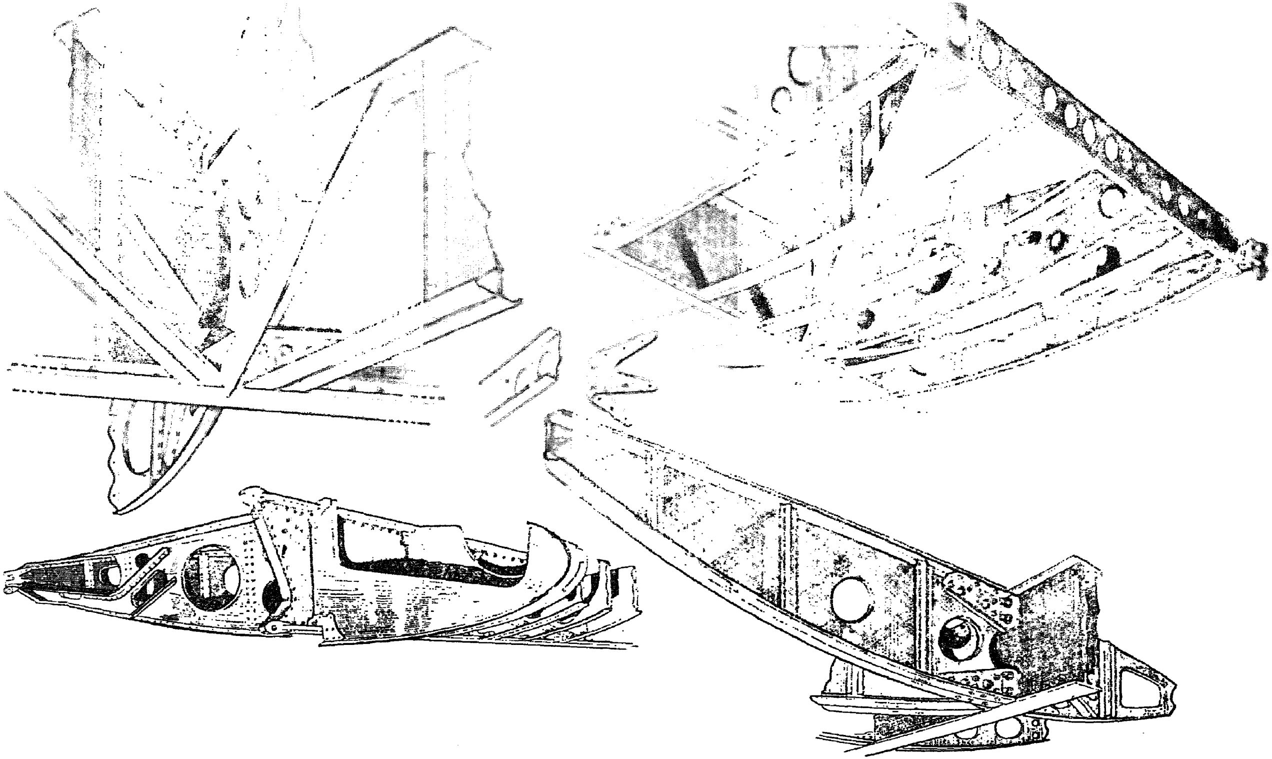


FIG. 147. LE O "45" WING CONSTRUCTION

(By courtesy of L'Aéronautique)



They are engaged in the construction of single-engine fighters and large four-engine aircraft of which it has been impossible to obtain detailed information. Their factories, however, are amongst the most important on the French Aircraft Industry.

PRIVATE FACTORIES. **Morane-Saulnier.** The Morane-Saulnier company has been producing single-seat fighters having interesting features. The MS. 405/6 have single spar wings of the type shown in Fig. 148.

The wing is braced in torsion by diagonal ribs, across which pass light profile members. At each apex of the diagonal system runs a main fore-and-aft rib. The spar consists of extruded flanges having a double "T" section and two flat plate webs attached to them by eyelets. The root joints of the outer section are made of high-tensile steel forgings capable of taking a load of 180,000 lb. in tension and compression on static test. (See Fig. 149.)

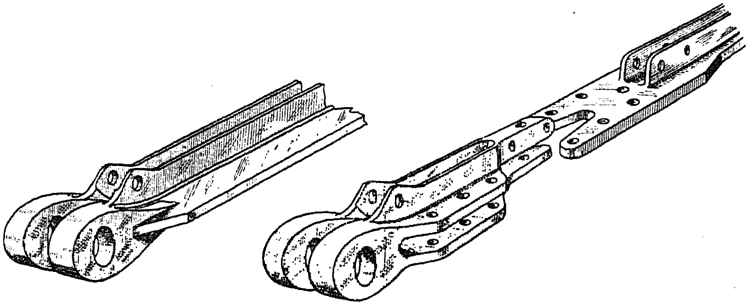


FIG. 149. MORANE-SAULNIER "MS 405/6" SPAR JOINT FORGINGS
(*By courtesy of L'Aéronautique*)

Société du Duralumin. The Société du Duralumin was formed in 1936 to build prototypes of the light plane class in duralumin. One of their first projects was the Allar 0·4, a two-seater machine having a pusher airscrew mounted on the rear end of the cabin cell, the tail being carried on twin booms, some details of which are shown in Fig. 150.

This illustration shows the robust construction of the centre section spar to which are joined the tail booms. These carry at their forward end the undercarriage, and at their rear end the tail plane and twin rudders. The main plane construction is extremely simple. In the heavier inner end, the spar consists of a flat plate web having angle flanges riveted thereto. Towards the tips it goes down to a flat plate with flanged edges. The flanges point aft, and on the front face there are angle strips riveted to the web which carry the leading edge. The leading edge is supported by built-up angle ribs towards the centre section, and out towards the tip these are replaced by simple pressings from flat plate. (See Fig. 151.)

Another aircraft which has been produced by the Société du Duralumin is the Daspect 3. This is a single-seat machine of light weight. The wing is carried on two tubular spars of just over 3 in. diameter, the front spar being $\frac{1}{8}$ in. thick, and the rear just over $\frac{1}{16}$ in. The spars are joined by five drag struts of round tube as well as by the ribs, the covering being of fabric. The front spar forms the leading edge of the

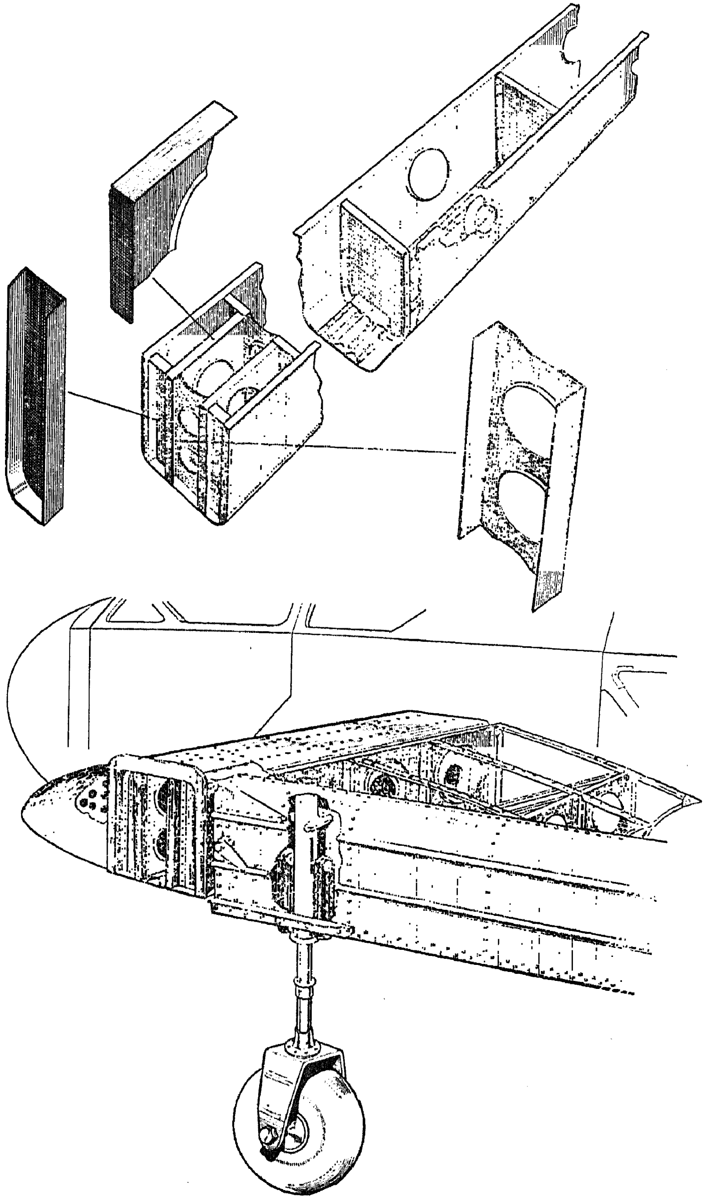


FIG. 150. ALLAR "0·4," SPAR AND TAIL BOOM STRUCTURE

(*By courtesy of L'Aéronautique*)

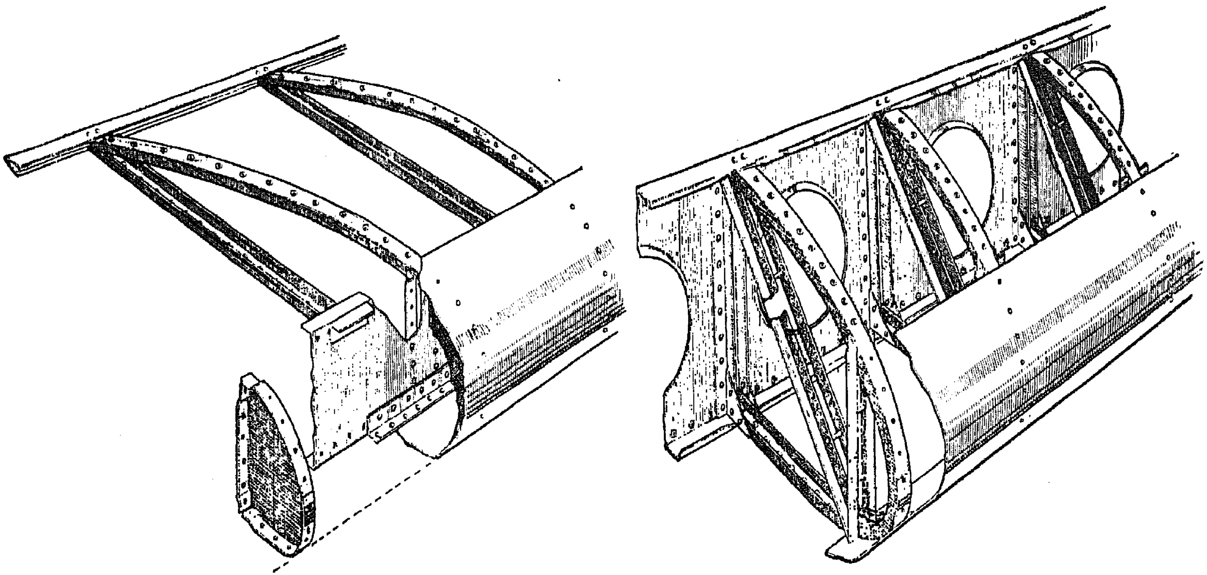


FIG. 151. ALLAR "0·4" SPAR AND RIB DETAILS

(*By courtesy of L'Aéronautique*)

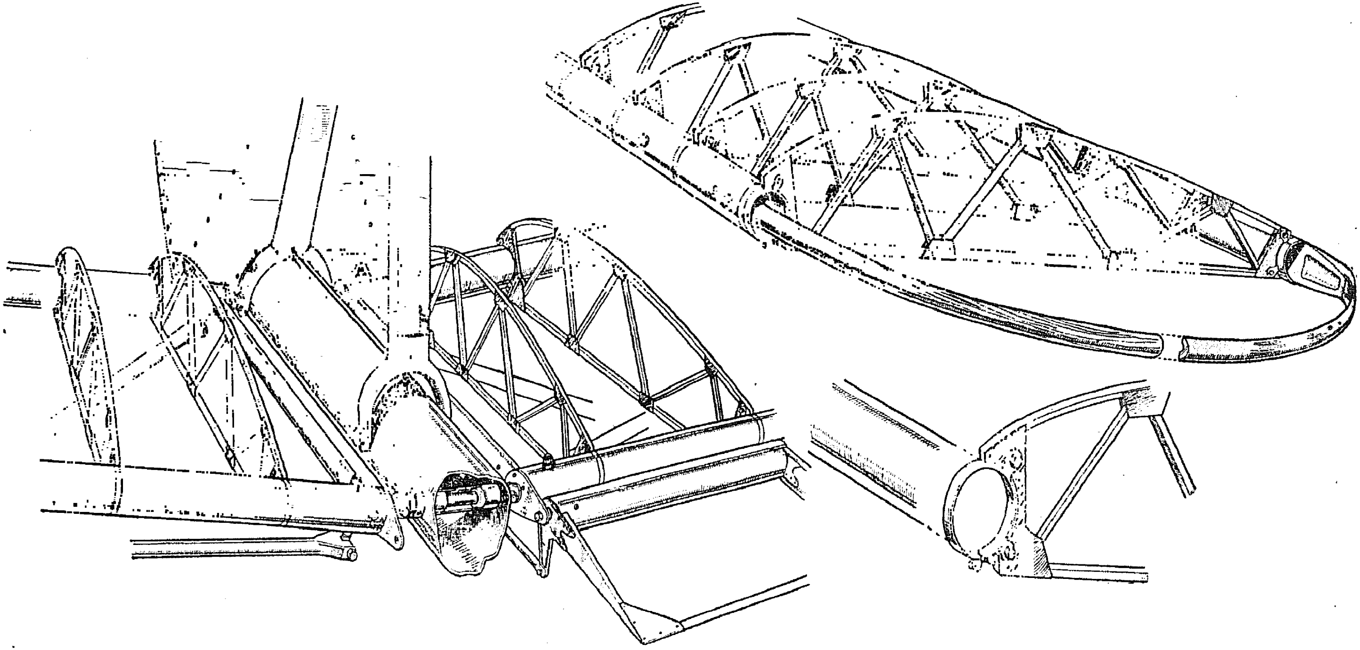


FIG. 152. DASPECT "3" WING STRUCTURE

(*By courtesy of L'Aéronautique*)

wing and the ribs are built up of square members with 3-ply gussets. This form of construction would not be appropriate to a high performance heavily laden wing. It is, however, extremely suitable for light aircraft. On a high performance aircraft it would be uneconomical in weight, and while the design will be particularly cheap to produce in small quantities, the enormous scale of modern military production allows of such expensive jigging that more refinement in the details is permissible. (See Fig. 152.)

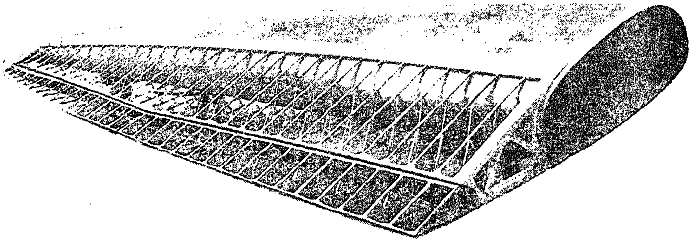


FIG. 153. KELLNER-BECHEREAU WING STRUCTURE

(By courtesy of Kellner-Bechereau)

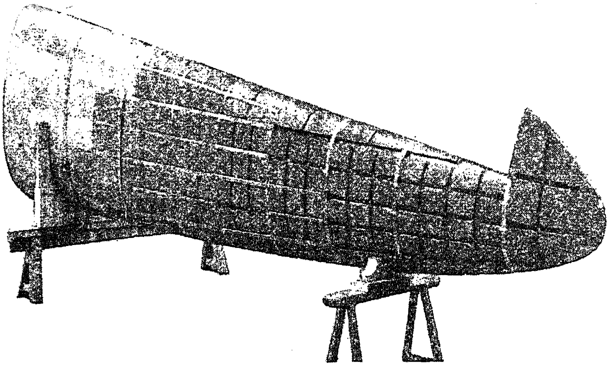


FIG. 154. KELLNER-BECHEREAU WING JIG

(By courtesy of Kellner-Bechereau)

Kellner-Bechereau. The wing of the Kellner-Bechereau monoplane has, virtually, a single spar. This is in the form of an elliptical duralumin tube, at the rear edge of which tubular ribs are attached, extending back to the aileron false-spar. The construction of such a tube (Fig. 153) would be extremely costly by ordinary methods. A method, however, has been devised which is very simple, cheap, and quick. A wooden mould is made as shown in Fig. 154. This has grooves cut in its surface to take the angle stiffeners which support the shell. The stiffeners are cut to the correct lengths and bent round into their respective grooves. The skin, made up of small plates, is laid on top and strapped into position. The rivet holes are marked out and drilled. The work is then taken down and re-erected away from the mould with the certainty that the holes will all match. At this stage the internal diaphragms are also added, the rivets are put in and closed in the ordinary way. The trailing edge is fabric-covered. This elliptical spar, which is, of course, of great torsional rigidity, has a weight of 1·16 lb. per square foot.

GERMANY.[1] The early work of Dornier, Junkers, and Rohrbach in pioneering metal aircraft construction is well known. It is discussed in detail on later pages.

The modern trend in Germany, as in other countries, is to develop the smooth-surfaced stressed skin cantilever wing. More recently, other firms such as Messerschmitt and Heinkel have changed over from wood to metal and their designs show that, though without great originality, they have adopted the best modern practice.

An interesting point to study in both the Heinkel He.112 and the Messerschmitt Me.109 single-seat fighters is the effect of aerodynamic and military requirements on the structural design. Both have retractable undercarriages and both have guns mounted in the wings outside the airscrew disc. In the Heinkel the undercarriage folds laterally inwards but in the Messerschmitt it folds outwards. In each case the wheel, when retracted, lies between the spar and the leading edge. The spar (in each example a single spar is used) lies far back in the wing section to give free stowage space. In the Messerschmitt it is 45 per cent of the chord from the leading edge. This leaves room for the gun, the muzzle of which protrudes through the leading edge, to be mounted in front of the spar. In the Heinkel, however, since the wheel folds inwards into a relatively wider wing section, the spar does not appear to be so far aft, and the gun (a 20 mm. cannon) is mounted behind the spar.

In each case the main spar has a flat plate web, supported by vertical stiffeners at the rib positions, and extruded flanges. The flanges of the Messerschmitt are of "T" section while those of the Heinkel are of two angles back to back. The wing covering in each is of flat sheet metal, flush riveted.

This type of single spar structure, in which the torsion is taken by the metal covered leading edge, is not suitable for multi-engined aircraft. The engine mountings break the continuity of the leading edge and thus in the larger Heinkel He. 111K twin-engine bomber a two spar construction is used, the outer spars being lattice girders similar to the Dornier spar shown in Fig. 155. The centre section spars are conventional flat plate girders with extruded section flanges. These are slid into the fuselage between double frames and then bolted in position. The centre section carries the tanks and engines, and the whole wing structure is metal-covered with flush riveting.

More particulars are available of the work of the earlier German constructors and this is described in greater detail below.

Dornier. The Dornier construction is illustrated in Figs. 155 to 157. The first of these shows a section of one of the *Do X* main plane spars at the junction with the wing strut. Although drawn steel strip was used in some of the earlier Dornier wings, this is constructed throughout of duralumin angles and strip; but it should not be concluded from this that light alloy will finally supersede steel as a material for all Dornier main structural members. It will be seen from the illustration that this

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[1] At the time this edition was being prepared it was difficult, owing to the political situation, to obtain adequate particulars of German aircraft.

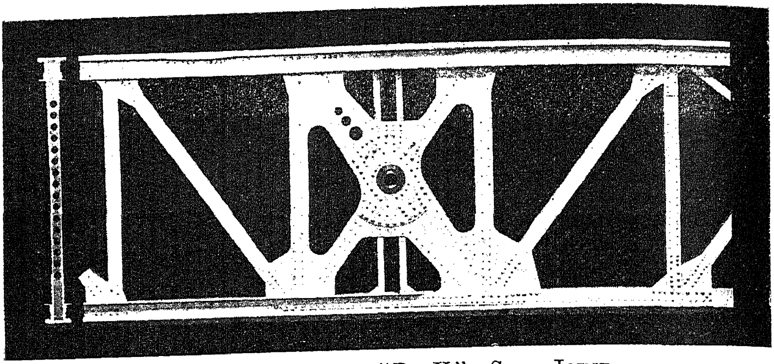


FIG. 155. DORNIER "DO X"—SPAR JOINT
(*By courtesy of Dornier Metallbauten G.m.b.H.*)

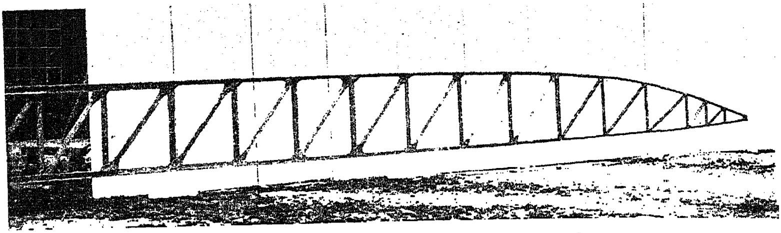


FIG. 156 DORNIER "DO X"—SPAR TIP
By courtesy of Dornier Metallbauten G.m.b.H.)

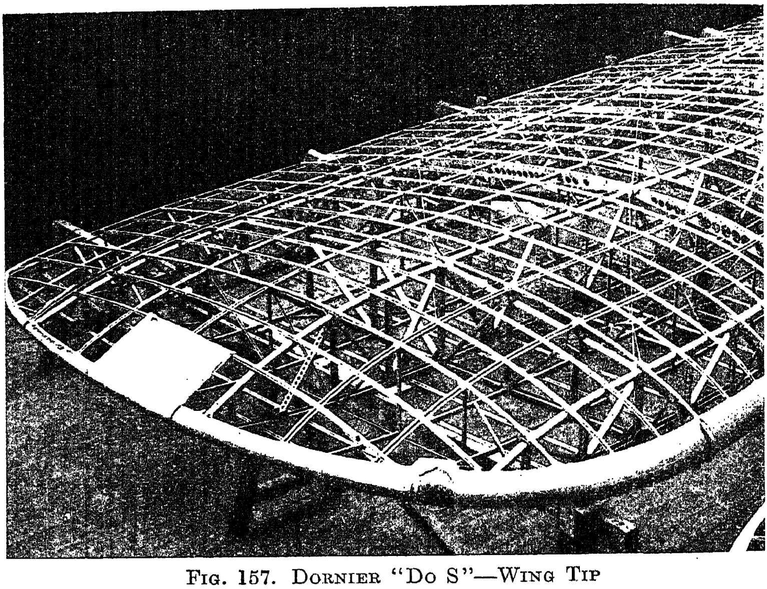


FIG. 157. DORNIER "DO S"—WING TIP
(*By courtesy of Dornier Metallbauten G.m.b.H.*)

spar is similar to that used by other firms in deep cantilever wing sections. Fig. 156 shows the overhang, and in particular the method used to attain the taper at the tip.

Fig. 157 shows the internal structure at the tip of the *Do S* wing. This consists of three deep lattice girder spars of the type shown above. In the longitudinal direction there are widely spaced girders joining the spars, forming rectangular panels which are cross-braced with wires just inside both upper and lower surfaces. Across these run channel sections (laterally) from tip to tip of the wing which carry light transverse formers of channel section. These conform to the wing profile and support the fabric with which the wing is covered. It will thus be seen that the air load passes from the fabric to the formers, through these to the lateral supports, and thence by way of the widely-spaced longitudinal members to the spars. For a time Dornier departed from a complete metal covering of the wing, and with the exception of the metal-covered leading edge, the wings were almost exclusively fabric covered. In the *Do X* the covering was made up in portable panels (Fig. 161). This subdivision on large machines not only allows easy access to the main structure, but facilitates replacement and repair.

The plan form of the Dornier main plane shown in Fig. 162 is original. It has been found that, whilst the semi-elliptical leading edge gives, very nearly, the ideal lift distribution, the straight trailing edge simplifies the construction of the aileron controls. This is an excellent example of the influence of constructional design on the aerodynamic lay-out of an aeroplane.

Later Dornier aircraft, such as the *Do* 17 and the *Do* 215 twin-engine bombers, show two lattice girder spars of the kind illustrated in Fig. 155. The flanges are extruded sections tapering towards the tip. The main ribs are of normal girder construction, built up of channel sections. A flush-riveted metal skin covers the whole wing, except for the under surface between the spars. This is fabric-covered.

Hamburger Flugzeugbau G.m.b.H. This company is a branch of the shipbuilding firm of Blohm and Voss and it builds seaplanes to the designs of Dr. Ing. Richard Vogt. A characteristic feature of the Hamburger aircraft is the single tubular spar wing, which closely resembles the Blackburn-Duncanson wing described on page 78.

Dr. Vogt argues that the advantages of this construction are apparent at the very outset of a new project. Since the spar takes both bending and torsion its exact position within the contour of the wing is not important. The leading edge is completely clear for the engine installation, which can be made very accessible. The concentration of the loads in a single relatively small member allows the use of a robust gauge of light alloy, or even steel, to which the attachment of fittings is simple.

For example, a catapult fitting capable of carrying a load of 110,000 lb. has been welded straight on to the spar shown in Fig. 158, without any of the elaborate structure which would have needed to disperse the load had a stressed skin structure been used.

Each float is attached to a single cantilever strut mounted by means of a flanged coupling to the underside of the spar.

Owing to the heavy loads in the centre section, this part of the spar is made of steel which is of sufficiently heavy gauge to allow the use of welding in assembly. Its joints are, therefore, petrol tight, and it is, in fact, used as a tank. In the H.A. 139 long range seaplane (Fig. 158) storage is thus provided for 1,430 gallons of petrol.

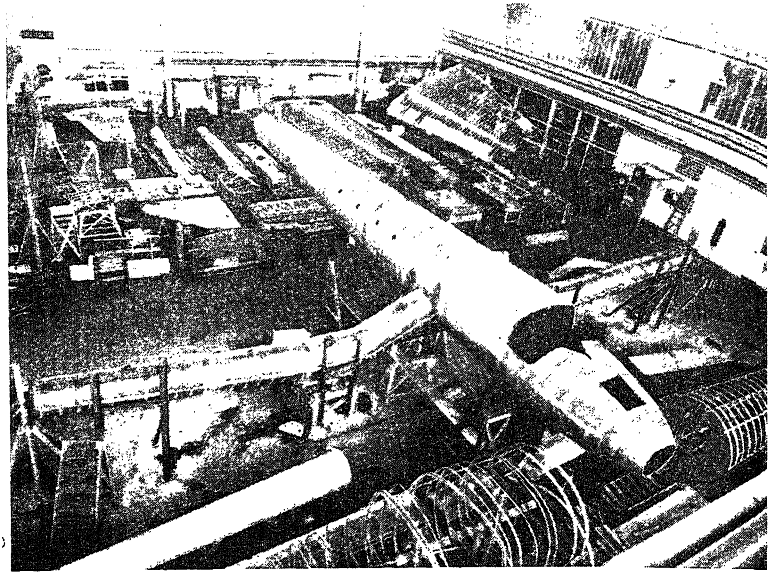


FIG. 158

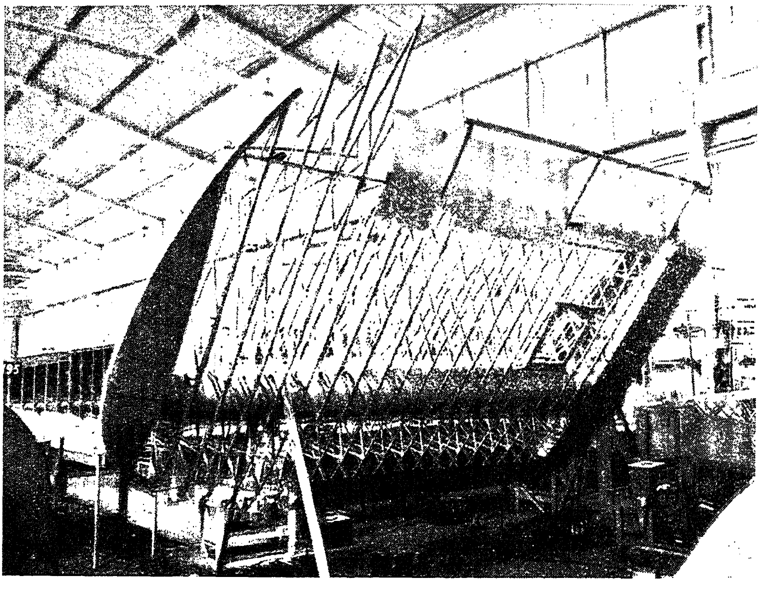


FIG. 159

FIGS. 158–159. H.A. "139" SINGLE SPAR WING

(*By courtesy of Blohm & Voss*)

The outer wing spar is built up of duralumin sheet, as shown in Fig. 160, which makes clear the three stages in manufacture. Although the stress from torsion would be evenly distributed round a symmetrical tube, the stresses from bending are concentrated on the upper and lower surfaces. These are, therefore, stiffened up by means of doubling plates riveted on.

The attachment fittings for the ribs are also shown in this illustration, and the complete assembly (without fabric covering) is seen in Fig. 159. One of the disadvantages of this type of structure is also apparent. It is not possible to use a wing which tapers straight to a narrow thin section at the tip since this would allow insufficient room for the spar. The outer wing is, therefore, thicker than is now usual, except for the last two or three feet, in which it tapers sharply.

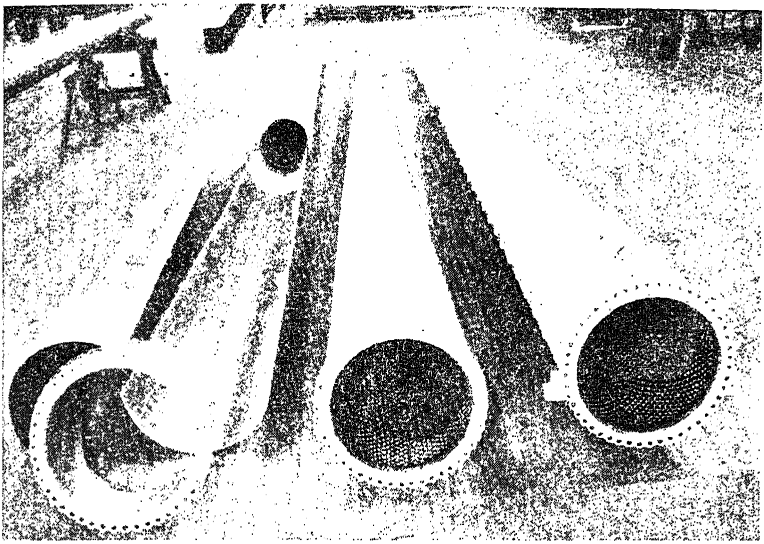


FIG. 160

(*By courtesy of Blohm & Voss*)

Dr. Vogt claims rightly that such a structure is simple to maintain and repair. Damaged ribs are easily replaced, and any dents in the spar may be hammered out and reinforced with patch plates, riveted or welded on.

Comparative weights and costs are not available.

Junkers. As early as 1910 Professor Junkers was investigating the problem of applying metal construction to a thick cantilever monoplane wing (see Chapter I). His first practical attempt to achieve this was during the War of 1914–18, when he built up a metal wing from sheet iron 0·1 mm. thick, welded together to the required profile. There was no internal structure and the whole load was carried through the skin, which was double. The outer side was of flat sheet and the inner corrugated, a system which has been revived in a modified form by various American constructors (see page 103). The construction proved

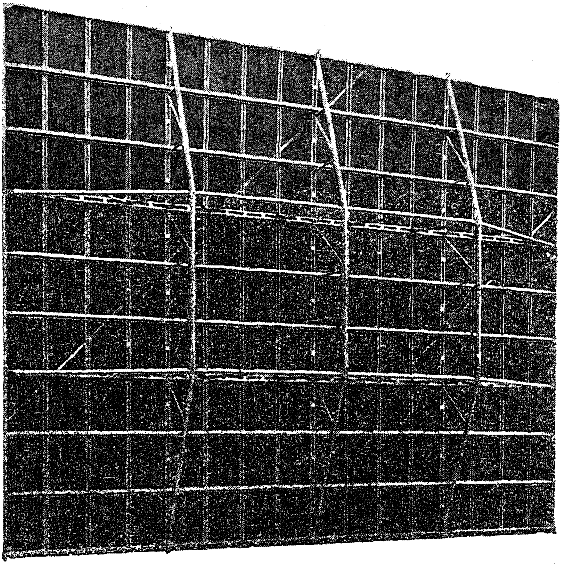


FIG. 161. H.A. "139" MAIN PLANE SPAR
(*By courtesy of Dornier Metallbauten G.m.b.H.*)

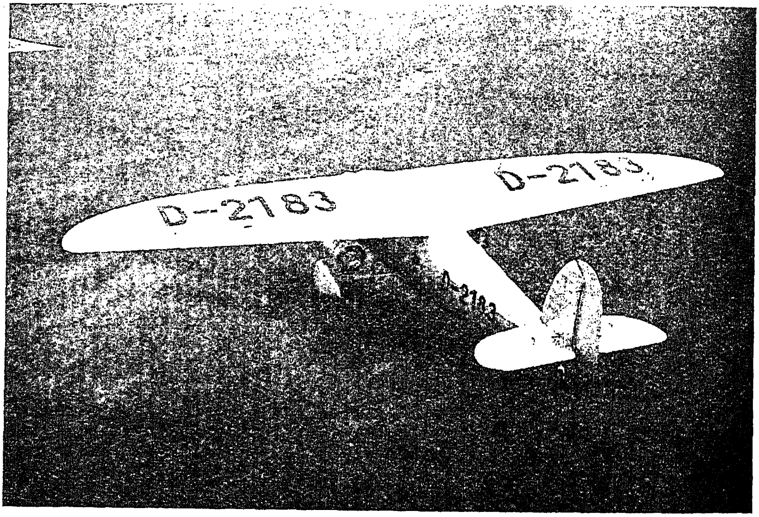


FIG. 162. DORNIER "DO K," SHOWING WING PLAN FORM
(*By courtesy of Dornier Metallbauten G.m.b.H.*)

to be extremely heavy and was abandoned. In 1917 he turned to duralumin and provided an internal structure of spars to carry the bending loads. No ribs were used and the wing was covered with duralumin sheets of single thickness, corrugated in the line of flight. This was immediately successful and the Junkers company developed the method on a large scale (see Figs. 164 and 165).

At the relatively low speeds used up to about 1932–3, the effect of the corrugations on the air flow was slight and the performance did not suffer unduly. At the Reynolds Number corresponding to the size and speed of modern machines, however, skin friction drag becomes of first importance and the corrugated skin has now been dropped. This is illustrated in Fig. 163, the outer wing of the Junkers 160. The two main spars each have two tubular flanges, webbed down each side with flat sheet. At intervals the webs carry vertical stiffeners which are in line with, and riveted to, the Z section stiffeners inside the skin. The leading edge which is carried on a single tube is swept back and the rear spar only is carried through to the tip. The under surface is cut away at the petrol tank and a loose panel bolted on. Tests have shown that if the bolts are closely spaced, such a panel contributes as much strength as if riveted.

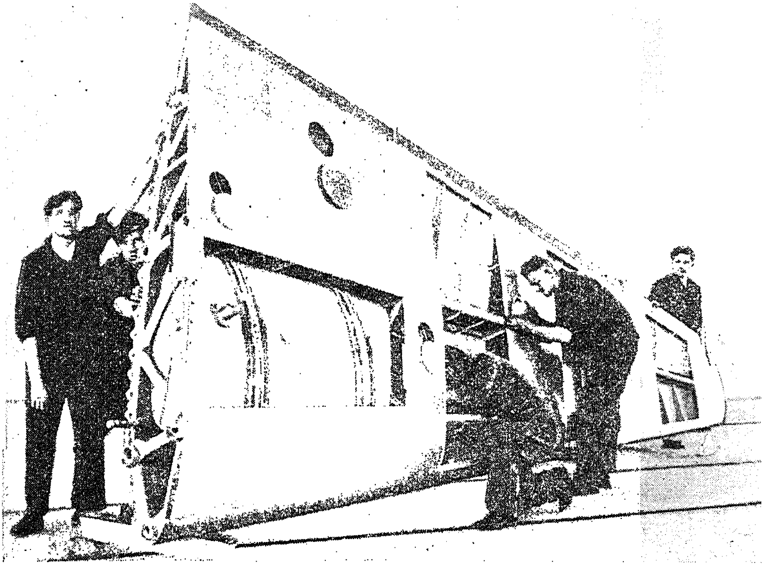


FIG. 163. JUNKERS "160" OUTER WING

(By courtesy of Junkers-Flugzeugwerk A.-G.)

A very practical point on which the whole construction depends is the riveting of sheet and bracings to the tubes. By developing special tools it has been found possible to use short rivets at any distance from the tube end. The holes are drilled, of course, from outside and the rivets inserted, to be hammered up against a rotating eccentric anvil inside the tube. This is manipulated by a remote control (Fig. 166).

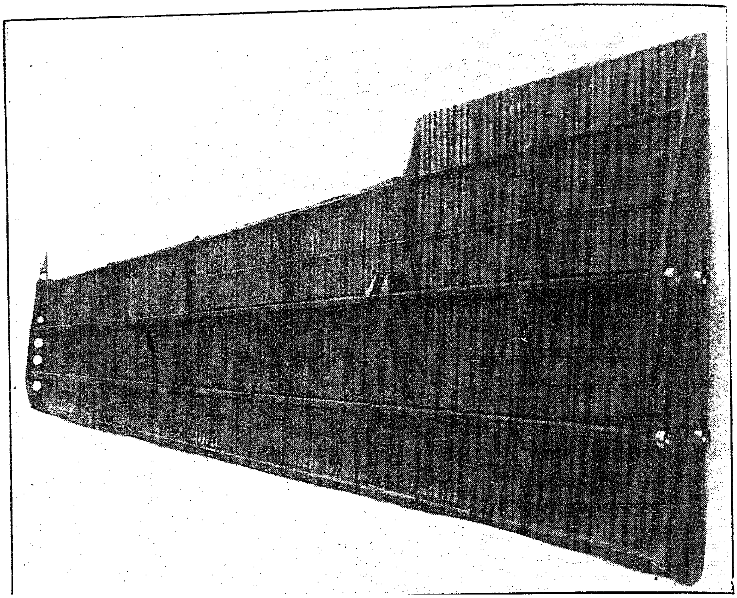


FIG. 164. JUNKERS "JUNIOR" MAIN PLANE
(*By courtesy of Junkers-Werke*)

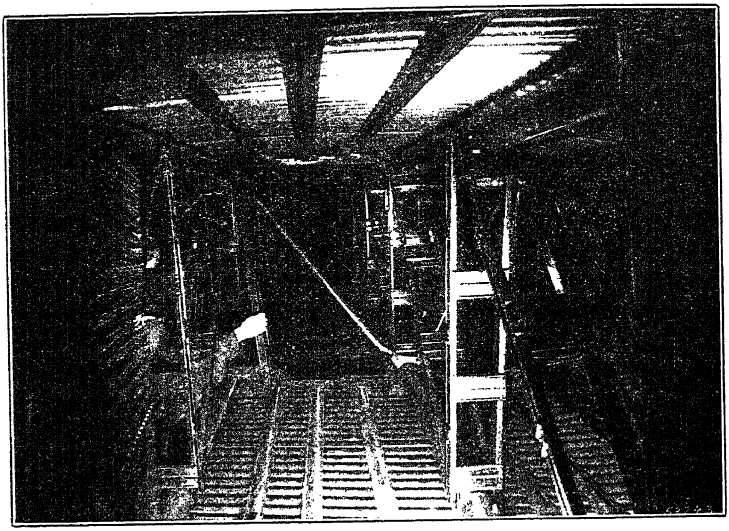


FIG. 165. INTERIOR OF MAIN PLANE, JUNKERS G.38
(*By courtesy of Junkers-Werke*)

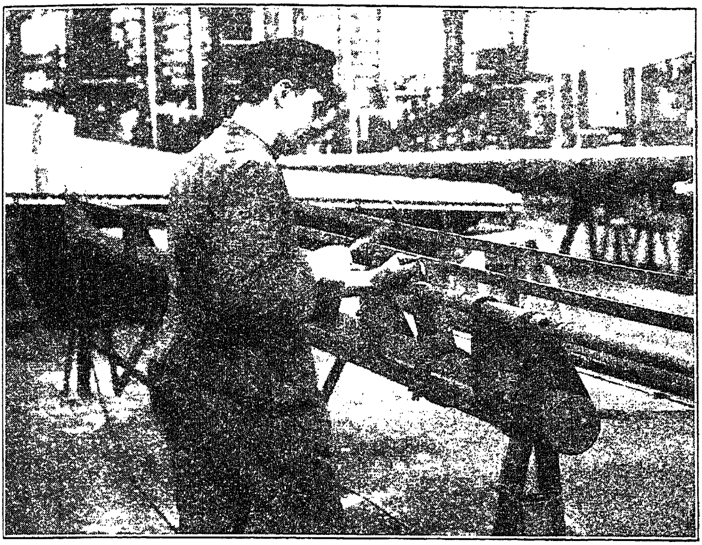


FIG. 166. JUNKERS SPAR TUBE RIVETING PROCESS
(By courtesy of Junkers-Werke)

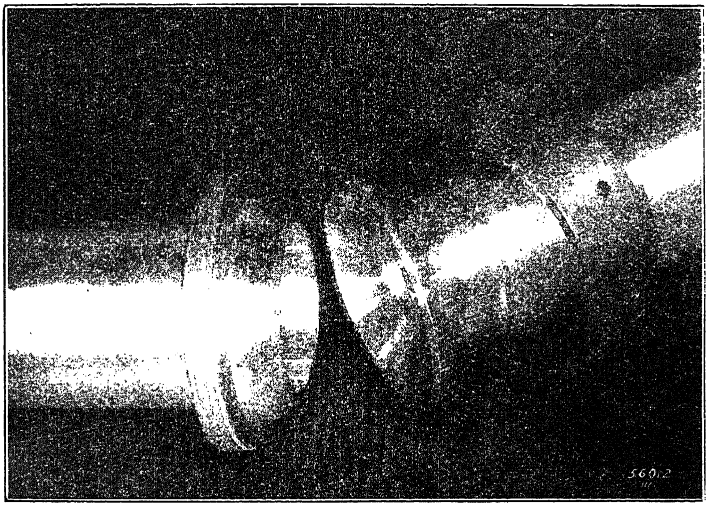


FIG. 167. JUNKERS TUBULAR SPAR JOINT
(By courtesy of Junkers-Werke)

It is only by the use of thick wing sections that Junkers has been able to achieve a pure cantilever monoplane. The multi-spar construction reduces the end load in each connection to a manageable quantity. The spar ends in the main plane are connected to the stub spars on the fuselage by spherical screwed couplings (Fig. 167). These are made of high-tensile steel and riveted into the spar tubes. The fuselage side in each case carries the male end.

Rohrbach. One of the pioneers, if not the originator, of the centre trunk wing was Rohrbach, who used duralumin throughout.

In the smaller machines the front and rear vertical walls of this box were well lightened, leaving the plates in the form of braced girders. The difference in width between the compression and tension braces will be noticed in Fig. 168. In the larger Rohrbach aircraft the vertical webs were not lightened out and the box spar was watertight (see Fig. 169).

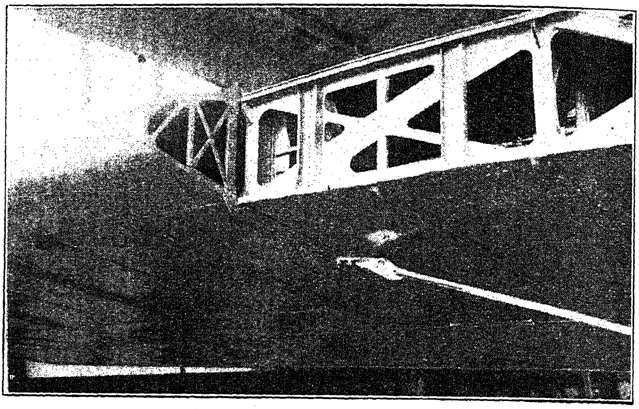


FIG. 168. ROHRBACH WING GIRDER CONSTRUCTION
(By courtesy of Rohrbach Metall-Flugzeugbau G.m.b.H.)

The plates were well stiffened with vertical channels. The top and bottom surfaces, which are of thick flat sheets, were stiffened with external closed channels riveted on.

To the main box girder were fastened lightly-constructed leading and trailing edges. These were braced structures built of channels covered with thin sheet metal. The fastenings were external to the wing surface, as will be seen most clearly in Fig. 168.

Rohrbach main planes were cantilever for about a quarter of the span from each tip. The lift member consisted of a double wire cable with single points of attachment at each end, which was attached at about a third of the chord from the leading edge.

Full scale destruction tests showed the box spar to be extremely stiff against torsion.

Some practical advantages of the Rohrbach three-piece construction were that the wing was easy to dismantle and transport. Production was economical since the work could proceed simultaneously on the several pieces without interruption. When damage occurs it is usually to either the leading or trailing edge piece, which may be quickly replaced without affecting the main girder.

ITALY. **Breda.** Another version of the thick section cantilever monoplane is seen in the Breda 32. The basis of the wing is a single spar from tip to tip. A centre portion is built across the bottom of the fuselage and the outer sections are removable, but the four socket joints on each side (see Fig. 171) provide for continuity of load whether in tension or compression. The spar may, therefore, be considered as continuous. The four corner members of this spar are cross braced with built-up struts which make it stiff both in bending and in torsion. The Breda designers do not favour the use of solid drawn tubes, since they feel that with built-up members they have greater latitude and can develop the maximum stress in all parts of the material. Each corner member is, in itself, a box of pressed or drawn aluminium alloy strip riveted. The bracing struts consist of back-to-back channels with side plates. The side plates have a centre corrugation to stiffen them and are lipped over at the free edges. Large corner gussets, well riveted to both corner members and bracings of the spar, fix the ends, thereby reducing the free deflection length on all the members when in compression.

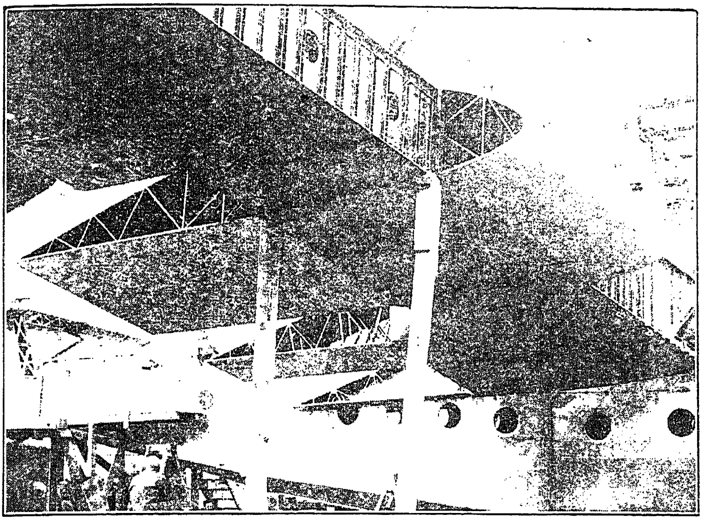


FIG. 169. ROHRBACH WING GIRDER, WITH LEADING AND TRAILING EDGES

(*By courtesy of Rohrbach Metall-Flugzeugbau G.m.b.H.*)

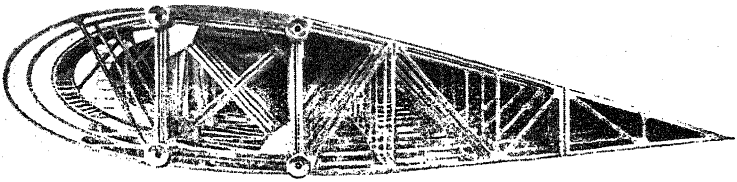


FIG. 170. BREDA 32—MAIN PLANE

(*By courtesy of Società Italiana Ernesto Breda*)

Ribs are built up of thin drawn duralumin sections bracketed to the spar and crossing it.

The wing is entirely covered in thin aluminium alloy sheeting

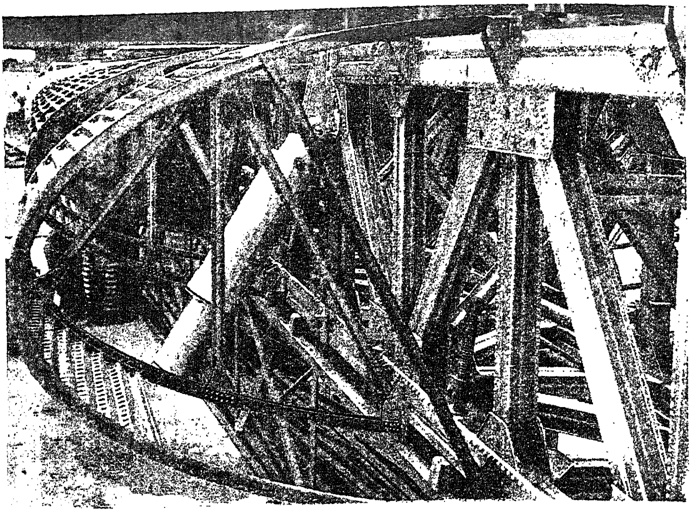


FIG. 170A. BREDA 32—MAIN PLANE SPAR

(*By courtesy of Società Italiana Ernesto Breda*)

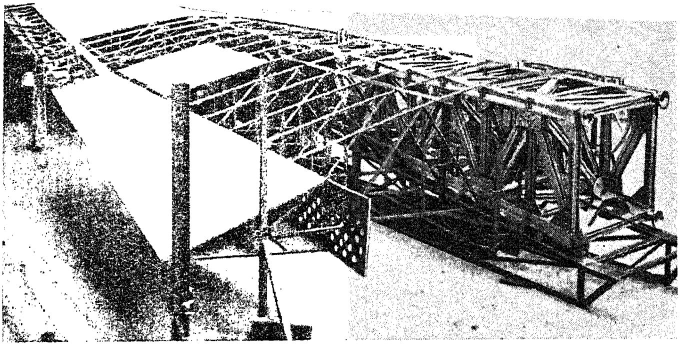


FIG. 171. BREDA 32—WING ROOT

(*By courtesy of Società Italiana Ernesto Breda*)

corrugated for rigidity. The form of corrugations is unusual, as will be seen from the illustrations (see also Figs. 219 and 220). This form of construction is extremely robust and the ratio $\frac{\text{all-up weight}}{\text{tare weight}}$ is 1·71.

The machine does not, therefore, pay for this robustness with excessive weight.

Caproni. The wing structure of the Caproni 101 trimotor monoplane is unusual in many of its details.

In general lay-out the wing is conventional, having two semi-cantilevered spars, tubular ribs, and fabric covering. Each spar consists of two tubular booms. These are separated by short vertical tubes of smaller diameter at regular intervals. The rectangular panels thus formed are cross braced with high tensile steel wires with fork ends. The junction of boom and bracings is made up with a low-carbon steel welded joint of the type shown in Fig. 247. This is soldered and bolted to the booms and vertical struts. The booms are made of nickel steel solid drawn tube. Although this is not weldable material, the low temperature at which the soldering is done does not affect it.

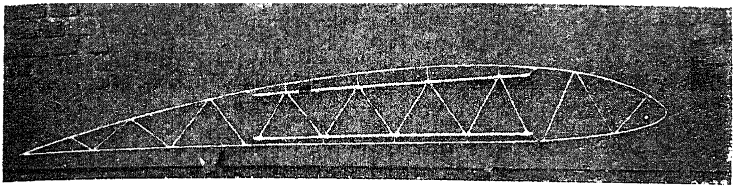


FIG. 172. CAPRONI 101—WING RIB

(By courtesy of Aeroplani Caproni Società Anonima)

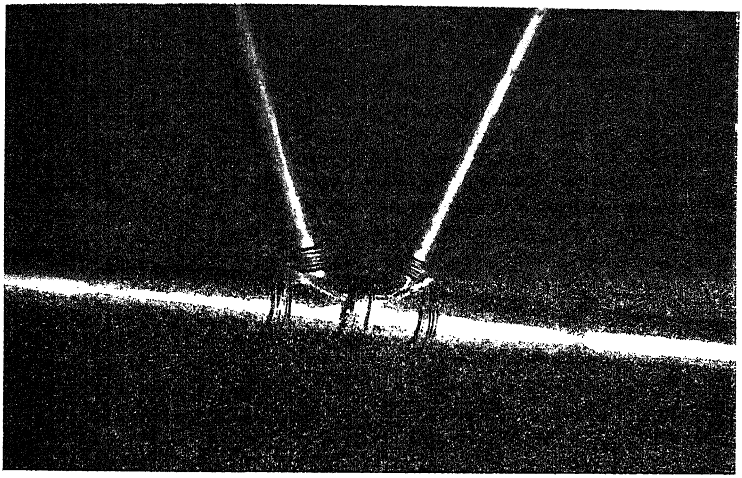


FIG. 173. CAPRONI RIB BRACING

(By courtesy of Aeroplani Caproni Società Anonima)

The rib construction shows an unusual feature in the two straight tubes which connect the corresponding front and rear spar booms. These are warren braced and run inside the curved profile tubes (see Fig. 172). A joint of the bracing and inter-spar tube is shown in Fig. 173.

The bracing ends are flattened down on to the main member and bound with steel wire, the whole being well soldered up. It is claimed that this method is simple, light, and quick, but it is, of course, only used where the loads are small. One of the main holding-down joints of wing spar to fuselage is illustrated in Fig. 174. Although the spar is not very clearly shown, the type of node described above can be seen in the middle on the sloping cross member which is the lower spar boom. This method of construction has no counterpart in British practice, and might be thought heavy owing to the redundances and the extra material in the form of sleeves at the joints. No wing weight figures are available, but the ratio $\frac{\text{all-up weight}}{\text{tare weight}}$ for the machine is 1·58.

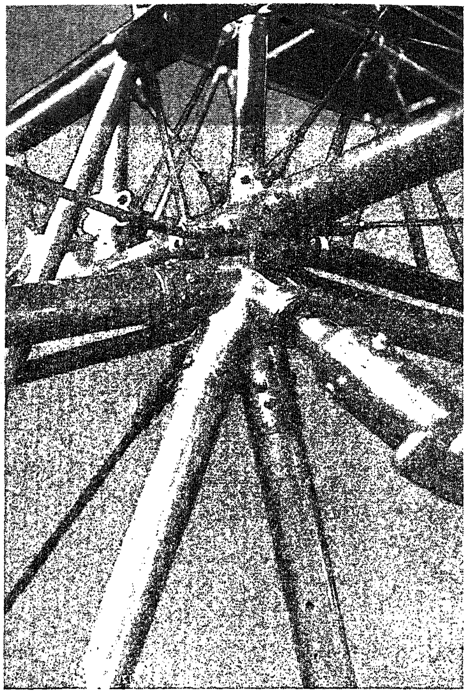


FIG. 174. CAPRONI 101—JOINT OF SPAR TO FUSELAGE

(By courtesy of Aeroplani Caproni Società Anonima)

The fuselage construction of this machine follows exactly the same methods and is described later.

Fiat. One of the best examples of the centre trunk described on pp. 28–29, applied to cantilever monoplane wing construction, is seen in the Fiat G.2 (Figs. 175 and 176, see also Fig. 222). The method is here used in its simplest form. The centre trunk consists of front and rear spars which taper with the depth of the wing, top and bottom surfaces and diaphragms, all of thin duralumin sheet. Leading and trailing edges are added. The spars are made strong enough to take the vertical bending, for, although a flat sheet web extends from top to bottc wing section, it is stiffened on both sides, top and bottom, with corrugated flanges, and has vertical stiffeners to prevent local buckling.

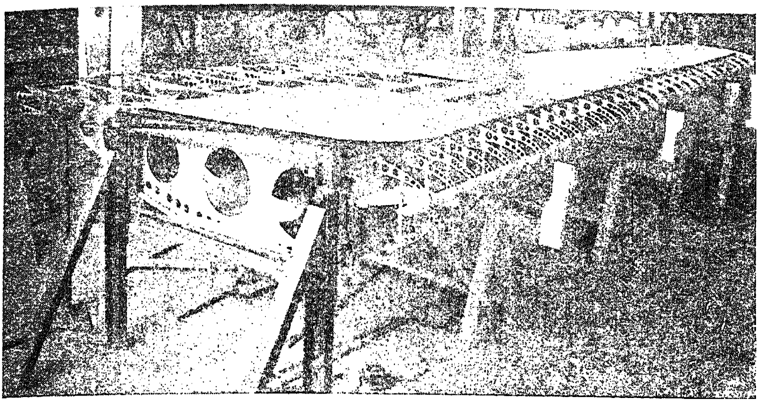


FIG. 175. FIAT G.2—MAIN PLANE CONSTRUCTION

(By courtesy of Aeronautica d'Italia)

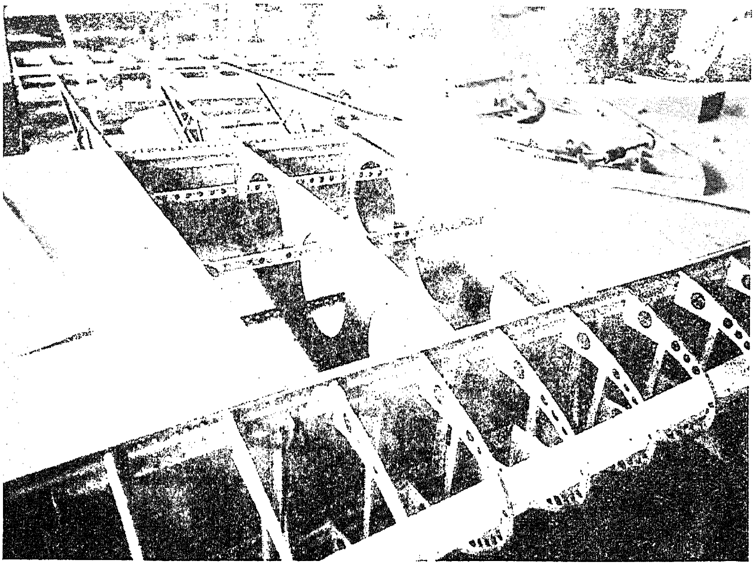


FIG. 176. FIAT G.2—MAIN PLANE CONSTRUCTION

(By courtesy of Aeronautica d'Italia)

The diaphragms, or ribs, are flanged top and bottom to take the riveted attachment of the skin, and have large lightening holes. Further spars. The centre section is based on a built-up tubular structure of high-tensile steel. The vertical and horizontal bracings between the spars are in Warren girder form, the short lengths of tube having end sockets fastened into them by tubular rivets.

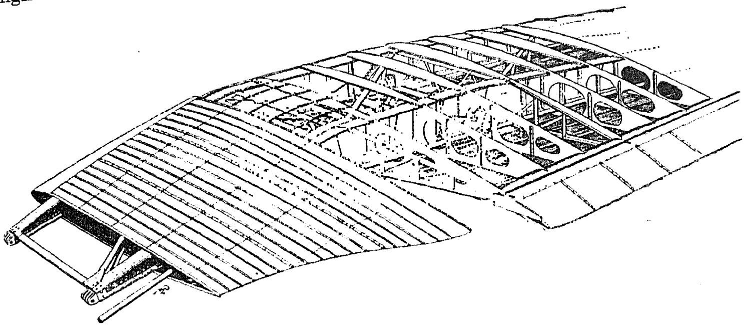


FIG. 179. POLISH P.Z.L. FIGHTER—MAIN PLANE

(*By courtesy of "L'Aéronautique"*)

The bare structure on its assembly jig is shown in Fig. 177. An

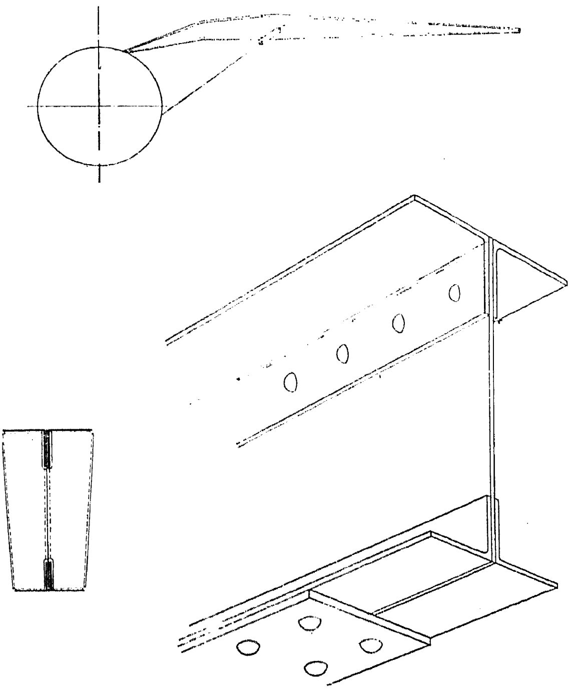


FIG. 180. GENERAL ARRANGEMENT OF SPAR IN RELATION TO FUSELAGE
WEB AND FLANGE STIFFENERS TO WHICH ARE FASTENED THE RIBS
SECTION OF SPAR

impression of strength and rigidity is given, but the ratio of weight of joints to weight of tubular members must be very high and the machined fittings on the spars very expensive.

Nardi. As in the Fiat G.18 V, described above, the Nardi F.N.305 has a tubular steel centre section. The aircraft, however, is a two-seater trainer and the loads are relatively small. There are two spars and those of the centre section cross the fuselage in one piece. They are welded up as shown in Fig. 178 and little weight is used in transferring the loads from one member to another. The only concession of this kind is found where the bracings meet the upper flange tube, a stiffening plate being welded to the boom locally.

A similar spar used in the Curtiss *Kingbird* has already been described on page 39. In that example, however, it was used for the outer sections of a braced monoplane where the loading was probably much less. Welded steel tube wing spars of this kind are usually found to be heavy unless they are justified by high loading.

The outer sections of the Nardi F.N.305 are of wooden construction and a discussion of them is not therefore appropriate to this book.

POLAND. **Polish National Aircraft Factory.** The Polish P type, Fighter class, had an unusual wing construction which presented a number of extremely interesting features. It had two spars of duralumin girder construction, normal ribs and a thin metal skin attached in strips from front to rear with upstanding flanges riveted through a continuation of the rib which stood above the wing surface proper. The spar flanges were of extruded angle sections riveted to a flat plate web. Over the centre portion of the spar, round the lift strut attachment, the flange was strengthened by a thick doubling strip riveted on. At the rib positions there were flange and web stiffeners bent up from flat plate. These were riveted on both sides of the spar. The spar was tapered in every direction and the flange angles were gradually reduced in width and depth towards the end. Where required for compression, the upper flange was wider than the lower. At a first glance it would seem that the end load in the inner bay, due to the lift strut, would, owing to the curve of the spar, augment the bending moment in this length. It appears, however, that the overhang bending moment was so large that this was counterbalanced and the inner bay was only lightly loaded. The neutral axis of such a spar is not necessarily at the centre of its depth and the apparent curve may not be the same as the true one.

Between the spars, the ribs were built up of angle sections riveted at their nodes. The upper and lower booms ran straight from spar flange to spar flange and carried above a strip of duralumin sheet which conformed to the wing contour and extended above it sufficiently to provide a foundation for the skin riveting mentioned above.

In some of the later Fighters of this type, the method of attaching the skin was altered and instead of having external riveted seams, which stood above the surface at the rib positions, the covering was laid on flat, the laps being riveted directly through the rib flange. The corrugations were also omitted, leaving an entirely flush surface.

CHAPTER IV

FUSELAGES

THE methods which have been employed or are possible for constructing fuselages are extremely diverse. Let us first consider the purposes of a fuselage and the forces acting on it.

The forward end is designed to carry an engine, except in certain twin- and multi-engined aircraft, where it becomes merely a fairing in front of the pilot's cockpit. As an engine mounting the structure must be extremely rigid and capable of withstanding the thrust and torque reaction of the power unit in addition to its weight vertically, and sideways when the machine is banked over. Owing to its position it is liable to more damage than any part of the machine, except the undercarriage, in bad landings. The engine mounting should, therefore, be easily replaceable, a condition which has additional excuse when two or more different types of engines might be alternatives, each requiring a different mounting. Not only must it fulfil these requirements and carry the engines satisfactorily, but it must also do it in such a way as to leave all the vital parts easily accessible. The cowling, and possibly radiator, must be attached to it, and all the engine equipment, such as filters, controls, fuel, oil and water pipes, and ignition wires, fastened on by clips.

The engine mounting is separated from the fuselage proper by a fireproof bulkhead of thin asbestos board, sandwiched between aluminium sheets. Coming now to the centre portion, we find it acting as a bridge between the engine loads in front and the tail loads behind. Through this centre section the whole weight of the aircraft must be carried to the main planes when in flight and to the undercarriage when landing, whether on one wheel or both. This part of the fuselage is the nerve and brain centre of the whole machine. In it are contained the pilot and all his controls, the fuel (unless it be in the wing), the passengers and cargo if a commercial machine, and the military equipment if for war purposes. The interior must be as clear of cross bracing and other such structure as the commercial or military requirements dictate. The outside, which acts as a weather protection to the people and goods carried in the machine, will be pierced with cockpit openings, doors, windows, camera and bomber's hatchway, and the like.

The rear end of the fuselage must carry the tail and transmit its loads to meet their reactions forward. These loads will be vertical from the tail plane and elevator, horizontal and torsional from the fin and rudder, vertical and possibly torsional from the tail wheel.

Finally the fuselage as a whole must be a streamline shape with fair lines from front to rear, and without excrescences, hollows or other obstructions to the air flow. It must be of as small a cross-sectional area as is consistent with its contents.

Such are the functions of a fuselage. Turning now from its functions to its qualities, the first consideration appears to be that it must be light in proportion to the work required of it. This quality, however, must be tempered with other and possibly contradictory ones. Weight, or the lack of it, is not everything. The structure must be strong, rigid and robust. Some thought should be given to the duties which the aeroplane is to carry out. An interceptor fighter which in war may be obsolete and liable to replacement after a few hundred flying hours is in a different class from a commercial freight carrier, which may still be working hard after five or more years' service. In the first case, weight and performance are of more importance than initial expense or maintenance costs. In the second case, robustness becomes a serious factor, and some sacrifice is to be made in getting it.[1]

Robustness and maintenance considerations, then, are qualities which may react on the weight of a fuselage. Only experience of any particular type of design can tell the designer which parts must be stiffened up to withstand rough usage. It would be obviously wasteful to stiffen up all members irrespective of their work.

The next important problem is that of production, considered in relation to the number of machines to be built from the design. Large quantities may make elaborate details more economical, and the apparently simple fitting may be expensive when more than one are required. This may sound paradoxical. Consider for a moment a wiring shackle such as is illustrated in Fig. 455. If a thousand were required, the cost of making dies for a drop forging would be small when spread over that number. If only one is required, it may be knocked up from plate and welded at a fraction of the cost of the forging dies. But in large numbers, the production of the bent plate fitting could only increase in proportion to the number of workers engaged in making them. No law can be made on the cost of manufacture. It depends on the plant available and the size of the order. And the design must accommodate this fact.

Finally, there is the question of replacements. A structure might be both light and robust; easy to maintain in service and cheap to produce, yet, when wear or damage occurs to a part of it, most difficult to repair. The fuselage may be one of a large batch in which it was found both cheap and light to use special high-tensile steel bolts. Should a single one of these be damaged when the machine is operating a long way from its base, the aircraft may be put right out of service for weeks. This example is admittedly an extreme one. Nevertheless it indicates a type of mistake which is too often made.

Considering all these functions and qualities desirable and necessary, it is not surprising that the methods of tackling the problem should be as diverse as the number of designers who have attempted to do so. But these methods submit to classification, and will be dealt with under main headings with variations of each. The two principal types into which fuselage structures may be divided are—

(*a*) Monocoque.

(*b*) Braced structure, with an unstressed fairing or covering.

There are many subdivisions of these classes, and many, too, which are border-line cases with features of both.

In recent years the number of aircraft with monocoque fuselages has far exceeded any other type. Yet the exceptions, and the reasons put forward in support of them are so important that they justify very serious consideration.

---

[1] The late Mr. Guilonard, Chief Engineer of the K.L.M. Air Lines, claimed that their Fokker equipment cost a negligible amount in maintenance and that machines were still satisfactory after many years' service. Had they been of lighter construction, the profit from the small extra pay load would have been absorbed in upkeep.

MONOCOQUE

The monocoque fuselage has been devised to do the greatest amount of work with the smallest number of members. It is undoubtedly a most attractive proposition to build a structure in which every part is doing more than one job. The idea in its simplest form is to have a hollow metal shell which shall be of streamline shape, and which carries all the loads imposed on the fuselage. And a shell of this shape is well fitted to do so. Being circular or elliptical in cross section, it is ideal for carrying engine and tail unit torsion, and quite satisfactory for bending loads, especially when the skin is thickened up to points of high stress.

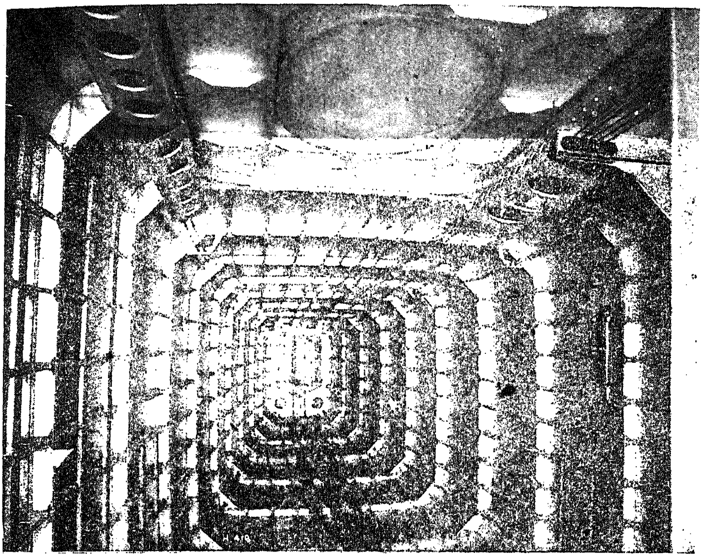


FIG. 181. INTERIOR OF "SHORT" VALETTA
(By courtesy of Short Brothers (Rochester and Bedford), Ltd.)

The nearest approach to the theoretically efficient shell was in some of the machines, such as the *Silver Streak*, *Satellite*, *Mussel* and *Springbok*, built by Short Bros., Ltd., in the years 1923–25. After that the type in its purest form was left behind in England and the skin dropped in importance. It was found difficult to build lightly yet robustly without some sort of framework inside. Thus, as the skin became less important, the framework became more so. An example which serves to illustrate this point is in the Short *Valetta*, a float seaplane produced in 1930 by the firm which pioneered metal monocoque construction in this country. A photograph showing the interior of the rear fuselage is reproduced in Fig. 181.

The big loads from the main plane and floats were taken on to a very strong cross frame of the box girder type. The skin of 20 to 22 s.w.g. duralumin sheet was stiffened at close intervals by longitudinal stringers, which not only stabilized it, but helped very considerably in carrying the vertical and side loads of the tail unit.

The transverse frames at larger intervals preserved the cross section of the fuselage, no cross bracing was fitted, and the whole interior was very accessible. The complete absence of wire bracing entirely removed the work of rigging the fuselage in service.

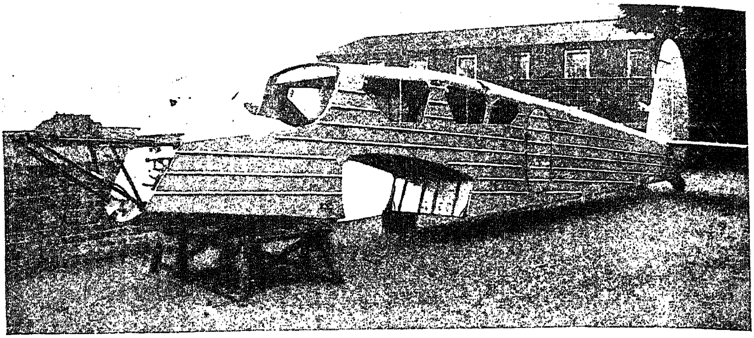


FIG. 182. SPARTAN CRUISER FUSELAGE
(*By courtesy of Spartan Aircraft, Ltd.*)

As the skin became of less importance so designers tended to make it thinner. In the example just considered flat sheets were used. But when a thinness of 24 s.w.g. is reached in duralumin, the sheet is unstable in flat expanses and cockles up at the slightest strain. However, by the subterfuge of ribbing or corrugating it, even thinner gauges may be made comparatively robust.

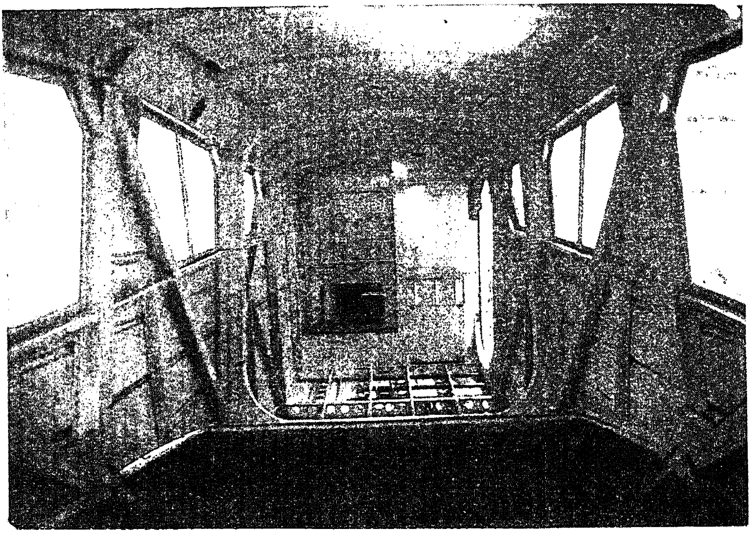


FIG. 183. SPARTAN CRUISER—INTERIOR STRUCTURE OF FUSELAGE
(*By courtesy of Spartan Aircraft, Ltd.*)

Another similar example is taken from the fuselage of the Spartan Cruiser. This was a low wing monoplane in which the main plane was built in one piece and passed through the fuselage unbroken, except for the leading and trailing edges. The cut-away for the plane is to be seen in Fig. 182, and also the attachments, three of which were situated on each side.

Whilst the "metal-clad" has a great overall rigidity it is not suitable for taking big localized loads unless specially stiffened. In this machine, therefore, the side panels of the centre portion of the fuselage were braced structures, and strong frames ran to the main plane attachments, so that the lift reactions were not taken directly into the skin. Towards the rear end, however, there were only transverse frames and bulkheads to preserve the cross-section. There were fewer longitudinal stringers than in the Short *Valetta*, but the skin had corrugations from end to end at intervals.

The centre engine mounting was of normal construction, and was attached to the front end of the fuselage by four bolts. This again caused a concentration of loads, but the diagonal bracing of the internal structure ran right forward and the skin did not take primary load here. At each point of concentration and junction of the diagonal members the skin was not considered adequate for gusseting, and an additional doubling plate was riveted on.

The material throughout this construction was "Alclad" and the rivets of duralumin.

More recently, however, there has been a noticeable return to the conception of the pure monocoque. This is illustrated in the Bristol 143, a low wing cabin monoplane (see Figs. 89 and 184). The concentrated loads at the wing roots are taken by carrying the two main spars right through the fuselage from side to side, gripping each between the webs of a double frame, which may be considered as a vertical extension of the spar to the top of the fuselage. Closely spaced stringers run across the two double frames fore and aft along the fuselage. At intervals there are transverse hoops or frames, which are riveted to the skin. They are notched to allow the stringers to pass through and there are no connections between the two except that provided by the skin.

The spacing of the stringers and frames is dependent on the thickness of the sheet and its curvature. Failure will most probably occur in buckling due to compression. The buckling stress may be expressed as:

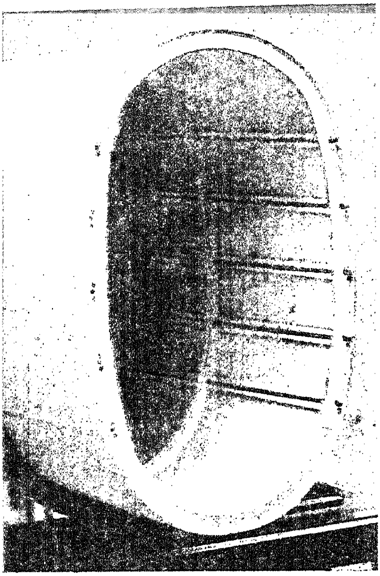
$$p = k \frac{E}{d/t} \text{ where}$$

k = a constant
E = Young's modulus
d = diameter
t = thickness.

Thus, where the fuselage is sharply curved in cross section a higher stress will be developed. On the relatively flatter sides of an elliptical cross section as shown in Fig. 184 the buckling stress would be lower. This accounts for the absence of stringers round the top and bottom of the section and their relatively close spacing along the sides.

It would thus seem economical both in internal stiffeners and in riveting to use curves of small radius and to avoid flat surfaces. At the same time this will involve double curvature and panel beating unless a straight taper is used. In the following pages, many examples will be seen showing the differing views of designers on this question. Apart from considerations of strength and cost, a slight amount of camber will remove the ugly wrinkles which are usually found in an otherwise flat sheet.

In general, the monocoque and metal-covered fuselages closely resemble flying boat hulls in their construction, and readers are referred to Chapter V for further remarks relating to the subject. The riveting of such structures is dealt with in Chapter IX.



istol 143 Fuselage
esy of "*Flight*")

A point of difficulty in fuselages of this type lies in their stressing. The distribution of stress in the skin and the strength which may be developed in it are difficult to solve mathematically, although empirical formulae have been evolved. It is not difficult to make a structure which is strong enough, but it is not easy to say when it is an economical one with every part doing work to the limit of its capacity. A full scale test therefore becomes necessary, with all its attendant expense and trouble, particularly if unforeseen failure occurs at an early stage in the test. In the large production of a type there is more argument in favour of proof testing, since all fuselages subsequent to the first may be modified in the light of the experience gained in the test.

If the fuselage is small the rig may not be unduly complicated. A Bristol fuselage was tested as shown in Fig. 185. The front end of the monocoque portion was held in a strong girder frame, the attachments being through the same fittings as are normally used for the main planes and engine mounting. A strong channel representing the stern post was rigged at the rear end. An up-load was applied to this through a screw jack, the downward reaction being taken on a weighbridge. The test could then be carried either to a proof load or to destruction. The proof load required by the Air Ministry for civil aircraft[1] is the specified unit external load multiplied by 62·5 per cent of the specified ultimate factor. This load must be held for one minute, during and after which the component must still be airworthy.

The test may then be continued until the load reaches full factor + 20 per cent. which represents the worst case occurring in flight, allowing for the material being thicker and the workmanship better than standard. This load must be carried without collapse.

But if the test is being made not for airworthiness purposes but for design data, it should be carried through to destruction. Any parts which collapse may be patched up and the test continued. Both redundancies and weakness may be found in this way, and the effects of cockpit and other openings studied.

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[1] *Airworthiness Handbook for Civil Aircraft*, A.P. 1208, Design Leaflet B1.

The illustration shows the form of the test to represent the case of up-load on the tail. Fin and rudder loads apply both direct bending and torsion. These might be represented by turning the fuselage on its side and applying the screw jack under some point along the rear channel girder offset from the centre. In both cases the actual load applied is equal to the weighbridge reading minus the weight of the screw jack.

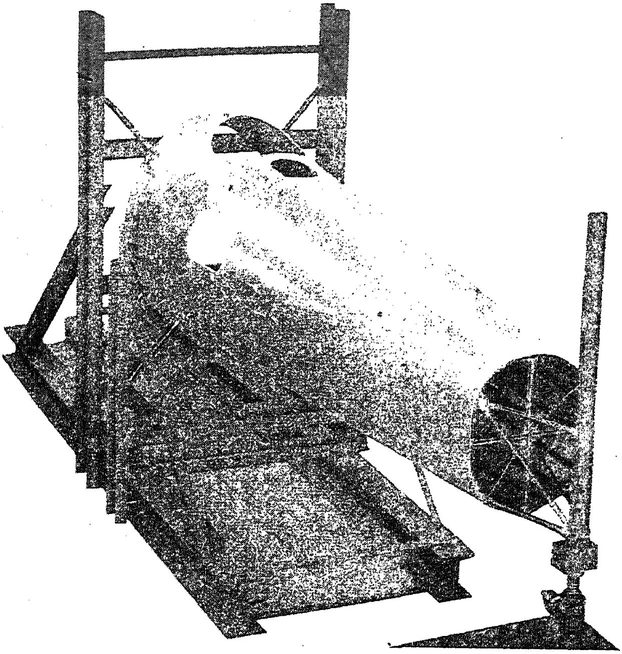

FIG. 185. BRISTOL MONOCOQUE FUSELAGE—TEST RIG

(By courtesy of the Bristol Aeroplane Co., Ltd.)

The duralumin monocoque fuselage of the Supermarine S5 Schneider Trophy racer was also proof loaded. The test is shown in progress in Fig. 186.

The fuselage is supported through the wing root fittings on a trestle. Shot bags representing the engine and tail loads are applied as gravity forces at front and rear. In each case the loads pass into the fuselage at the same fittings which transmit them in flight. They must be in equilibrium to prevent the fuselage overturning.

The problem was simpler in the later Short constructions. Here is a framed structure which responds to mathematical treatment, though it is still doubtful how much strength is contributed by the skin. In the [illegible] type, tests would reveal what width of skin may be taken as acting in conjunction with the girders and frames, and what is its value as shear bracing. Such tests may be carried out on a sample panel made up before the main construction is proceeded with. The expense will be relatively small and the results fairly conclusive. It is impossible to generalize and lay down rules in this matter, since insufficient data have yet been collected and each different fuselage creates its own problems which influence the results.[1]

In all the actual examples of British and foreign monocoque structures which are described in this chapter, the longitudinal stringers are either extruded or drawn strip members of angle or channel section.

A suggestion that great economy in weight might be given by the use of tubular stringers led to an investigation at the Royal Aircraft

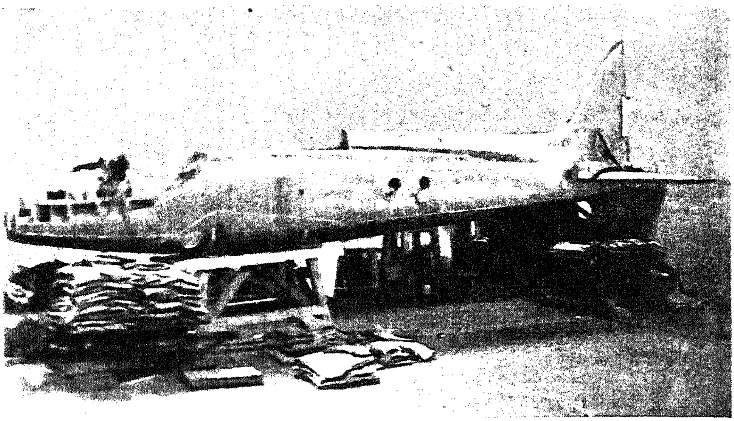

FIG. 186. SUPERMARINE S5 FUSELAGE—TEST RIG

(*By courtesy of Vickers (Aviation), Ltd.*)

Establishment, South Farnborough, from which some very interesting results were obtained.[2]

The reasons for suggesting the use of tubular stringers were, firstly, that being free from outstanding flanges or flanges riveted to the skin, they had a greater flexural and torsional stability; and secondly, that the mechanical properties of solid drawn tubes are generally superior to those of strip sections of the same material.

Tests were made on a series of panels using a representative range of sizes of tubular members with both the thinnest practicable skin and also a somewhat thicker one.

The conclusions reached are quoted—

"The investigation was directed towards the estimation of the bending strength of circular cylindrical shells reinforced with tubular stiffeners. The range of tests is representative of cylindrical shells

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[1] See R. & M. No. 1553, "Summary of the Present State of Knowledge Regarding Sheet Metal Construction," by H. L. Cox; also, "Some Developments in Aircraft Construction," H. J. Pollard, *Journ. R.Ae.S.*, July, 1934, and "Notes on the Strength of Stressed Skin Fuselages," Wallace, *Journ. R.Ae.S.*, April, 1936.

[2] "Stressed Skin Structures. Compression Tests of Panels with Tubular Stiffeners," by I. J. Gerrard, M.Sc., and B. G. Dickens, Ph.D. (R. & M. No. 1830).

3 ft. in diameter with 28 s.w.g. or 18 s.w.g. skin thickness, stiffened by various sizes of tubular stringers spaced at 4·04 in. circumferential pitch, i.e. 28 stringers per circle. The ring pitch in all cases is assumed to be 12 in."

The author's conclusions are as follows—

"Constructions incorporating solid drawn tubular stiffeners are lighter for a given strength or stronger for a given weight than constructions incorporating stiffeners formed from strip material.

"Comparative tests of panels with tubular and extruded angle stringers indicate that constructions using tubular stringers are 15 per cent more efficient on a strength/weight basis than constructions using extruded angle section stringers of similar material and weight.

"Within the present range of tests it has been shown that for a given skin thickness, pitch and weight of rings, an increase in the weight of tubular stiffeners produces a directly proportional increase in the failing bending moment of the complete cylinder.

"From the results given it is possible to estimate with reasonable accuracy the bending strength of circular cylinders of any radius and skin thickness stiffened by any of the sizes of tubes included in the present series at any given circumferential pitch, provided the rings or transverse stiffeners are adequate in stiffness and of 12 in. pitch. The results of a few tests on constructions incorporating one size of tubular or extruded angle stiffener indicate that 25 per cent and 50 per cent increases in the pitch of rings produce relatively small decreases in failing stresses.

"The stress developed in unstiffened curved duralumin sheet is given by the simple relation—

Stress in tons/sq. in. = 1,040 thickness of skin/radius, for values of thickness/radius up to 0·003 in."

So far there is no published evidence of any aircraft constructor having taken advantage of these test results. The gain to be had from them must be weighed against the difficulty of riveting the skin to small diameter tubes, particularly where these are curved to conform to the fuselage profile, and also the danger of hidden corrosion inside the tubes. If these difficulties can be overcome by the use of "pop" or explosive rivets, and by anodic treatment, then it would be valuable to compare a specimen fuselage built in this way with one of more conventional construction.

Armstrong-Whitworth. In most stressed skin fuselage structures, the longitudinal stringers run unbroken through the transverse frames, which are notched to receive them, and the skin is riveted to both stringers and frames. In the Armstrong-Whitworth *Whitley*, however, the ordinary transverse frames are simply hoops running across the inner faces of the stringers. The skin is thus attached only to the latter and the amount of riveting is greatly reduced.

The stringers, which have very little curvature, are of "top hat" section with both flanges attached to the skin. For the transverse frames, which have considerable curvature, an "omega" is used, this being easier to bend than the "top hat" (see Fig. 187).

The *Whitley* fuselage is not truly monocoque except at the rear end. There are four box girder longerons which gradually taper out. Heavy transverse frames are provided where the separate front and rear portions of the fuselage are joined to the centre section.

A long bomb compartment extends from the pilot's cockpit to some distance behind the centre section. Thus, over this length the structure is not a complete oval shell. and depends on the cabin floor to tie it across. This is made of sheet metal corrugated from side to side.

The centre section of the fuselage, to which the nose, or cabin, portion and the rear end are attached is actually part of the wing structure and is described on page 78.

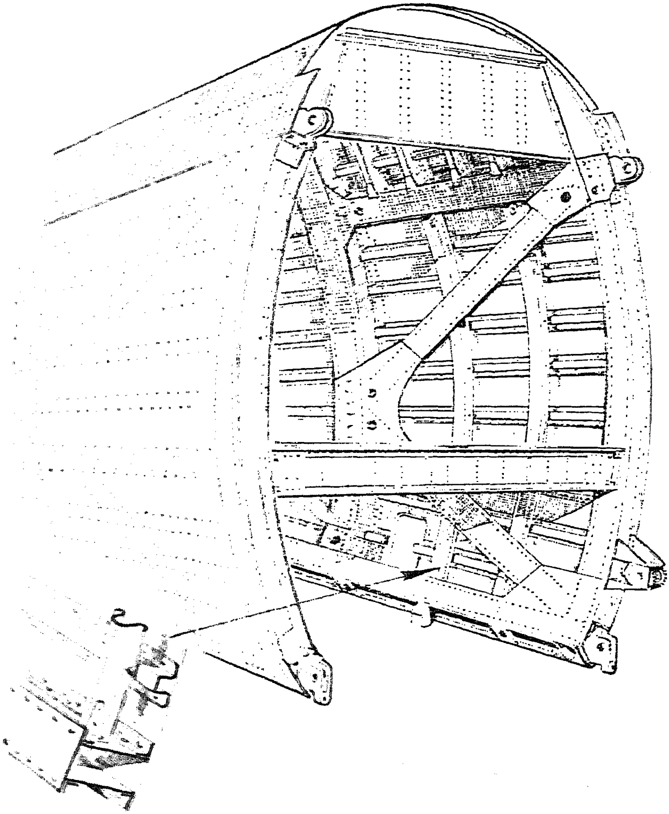


FIG. 187. ARMSTRONG-WHITWORTH "WHITLEY" FUSELAGE

(*By courtesy of "Flight"*)

De Havilland. The D.H. 95 (*Flamingo*) has a monocoque fuselage constructed entirely of aluminium alloy. It is made in two detachable sections, the first of which extends from the nose to behind the pilot's cabin. and the second from there to the tail.

The nose portion is shown in Fig. 188, and is built up on a framework of transverse frames of channel section. Each frame is pressed from "Alclad" sheet in short lengths which are overlapped and riveted together to form the complete frame. There are no longitudinal members other than a single channel along the bottom of the windows. In this nose portion are mounted the cockpit floor, controls, dashboard, and pilots' seats, before it is assembled on to the main length of the fuselage.

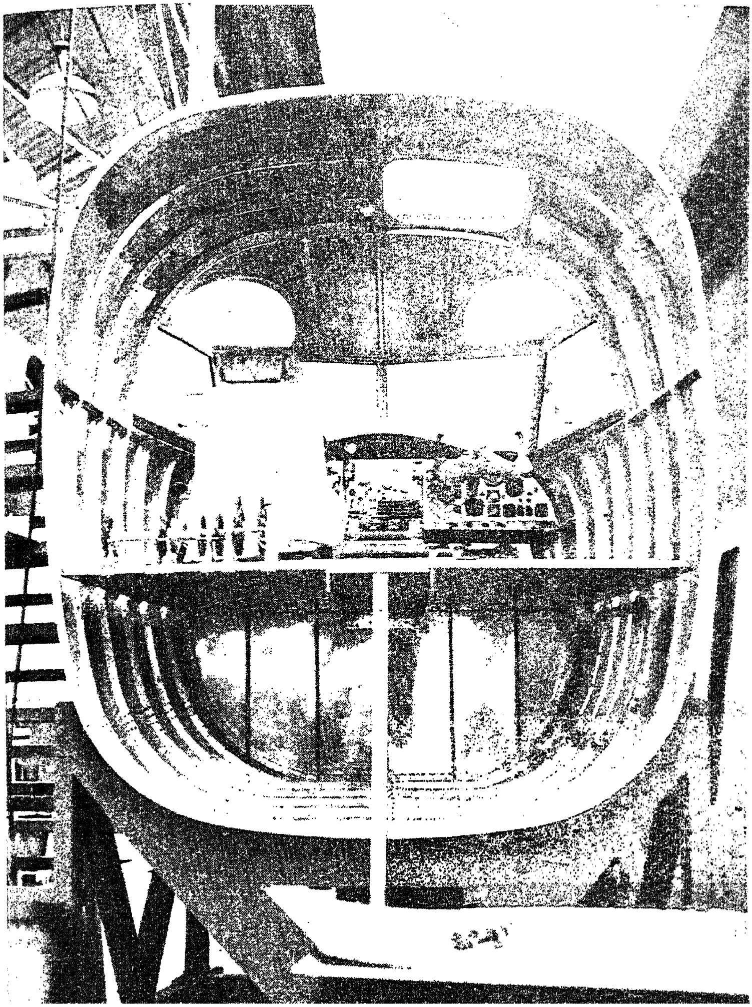


FIG. 188. DE HAVILLAND "FLAMINGO" FRONT FUSELAGE
(*By courtesy of the de Havilland Aircraft Co. Ltd.*)

The advantage of this system in preventing congestion of labour is obvious.

The main portion of the fuselage is, of course, more complex, particularly where the single main plane spar passes through and is joined to it. The spar, which was described on page 84, is a lattice girder, which

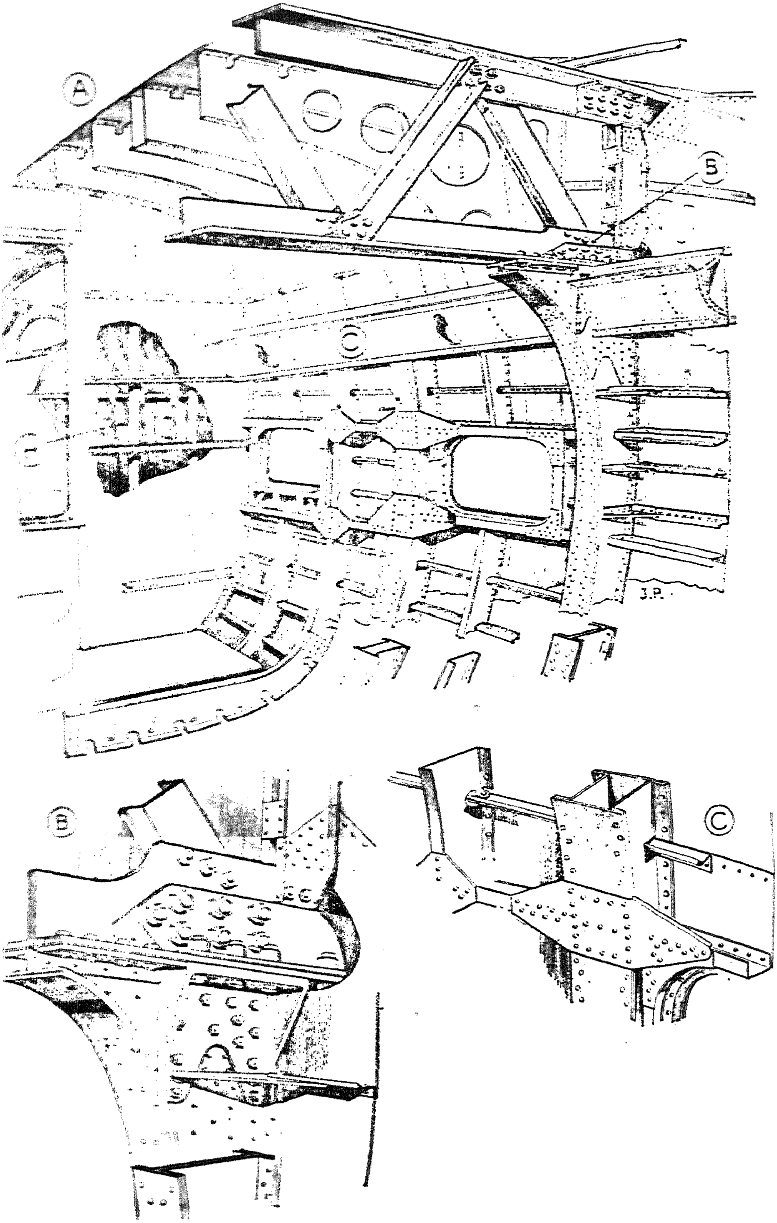


FIG. 189 DE HAVILLAND "FLAMINGO" FUSELAGE DETAILS

(By courtesy of "Flight")

is anchored down on to a strong frame, the joint being shown at B in Fig. 189.

The frame is a girder of double channel sections, back to back, with plates riveted to both flanges. At the top it broadens out to form a base for the spar attachment which is made through a forged box fitting, bolted on. The skin covering of the fuselage is cut round the lower flange of the spar and then riveted to a special web member introduced into the spar bracing.

Another strong frame is provided in line with each of two auxiliary spars in the wing, the forward one of these being shown at C in Fig. 188. These auxiliary spars do not themselves pass through the fuselage.

The ordinary lighter frames of the centre and rear fuselage are of channel section, notched to allow the extruded bulb-angle stringers to pass through unbroken. A point of practical interest here is that in cutting the notches a small tag is left, this being bent up and riveted to the stringer. For theoretical reasons it is not necessary to attach the stringers to the frames as all the stress can be carried from one to the other through the skin. The tag, however, serves to hold the stringers in position during the building of the structure, before the skin is put on. One of these tags can be seen in the lighter frame in detail C, Fig. 189.

Keel members and specially stiff frames are provided under the cabin floor to protect the passengers and the structure if it should be necessary to make a forced landing with the undercarriage retracted.

The shell plating is of "Alclad" sheet laid on in narrow longitudinal strips, with single riveted overlap joints along the stringers.

Fairey. The fuselage structure of the Fairey *Battle* is to outward appearance of clean but conventional design. There are closely spaced transverse frames which are each pressed in one piece from aluminium alloy sheet. They are of angle section, but the inward pointing flange is rolled over to stiffen its edge.

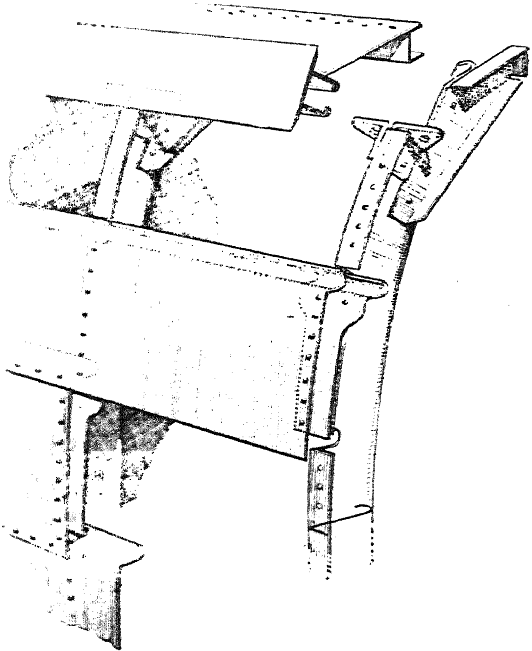
It is in its longitudinal stiffening that the structure is unconventional. No stringers are fitted, but the shell plating is laid on in narrow overlapping strips and one edge of each plate, the under one in the lap, is flanged over and then curled back. This forms, in effect, a stringer but it is economical in material and saves riveting (see Fig. 190).

Each length of plating must, of course, be broken owing to the difficulty in supplying and handling pieces of sufficient length to go from end to end of the fuselage. The joints in the lengths are made at transverse frames and a short single riveted butt strap is inserted under the joint. One piece of plating is riveted through both the flange of the frame and the butt strap, the adjoining piece through the strap alone. In addition to the flanged edges of the plating there are also four main longerons over the centre part of the fuselage, but these die out before the tail is reached. They are of π section, extruded from aluminium alloy. The upper ones carry the deck edge round the pilot's and gunner's cockpit and the lower ones pick up the wing root.

One of the problems in a monocoque fuselage is that of installing the equipment. In a braced structure covered with fabric or loose panels, this does not arise since the work is done through the open sides before the covering is put on. In the Fairey *Battle* the pilot sits right over the leading edge of the wing and the most complicated equipment is in his part of the cockpit. This portion, from the front wing spar position forward to the engine mounting, is therefore made as a braced ure and the covering is not put on until the equipment installed.

In the monocoque portion the equipment, wiring, piping, etc., are built up in sub-assemblies on jigs before being installed so that as little work as possible is actually done inside the fuselage.

Handley-Page. The fuselage construction of the Handley-Page *Hampden* is an excellent example of the way in which the practical



[illegible] Fairey "Battle" Rear Fuselage Construction
(By courtesy of "Flight")

problems of rapid and cheap manufacture can be solved in the drawing office. Too often these considerations are left entirely to the works who have to devise elaborate and expensive jigs and tools, after the design has been completed. The performance, the ratio of the useful load to the all-up weight, and the military effectiveness of this aircraft by comparison with others of its generation are such as to show that the policy of complete co-operation can be successful. Aircraft design is not only a matter of mathematics, aerodynamics, and the theory of structures, as one would imagine if one studied the curricula followed by many who are being trained as designers.

The fuselage of the *Hampden* is split up into three main units, a nose portion which includes the pilot's cockpit, a centre portion to the trailing edge of the wing fillet, and a rear portion. Of these, the centre and rear portions are further split down the centre line forming port and starboard halves. Each of these five pieces is made separately up to the point when the equipment has been mounted on them. They are then brought together in a final assembly (see Fig. 191).

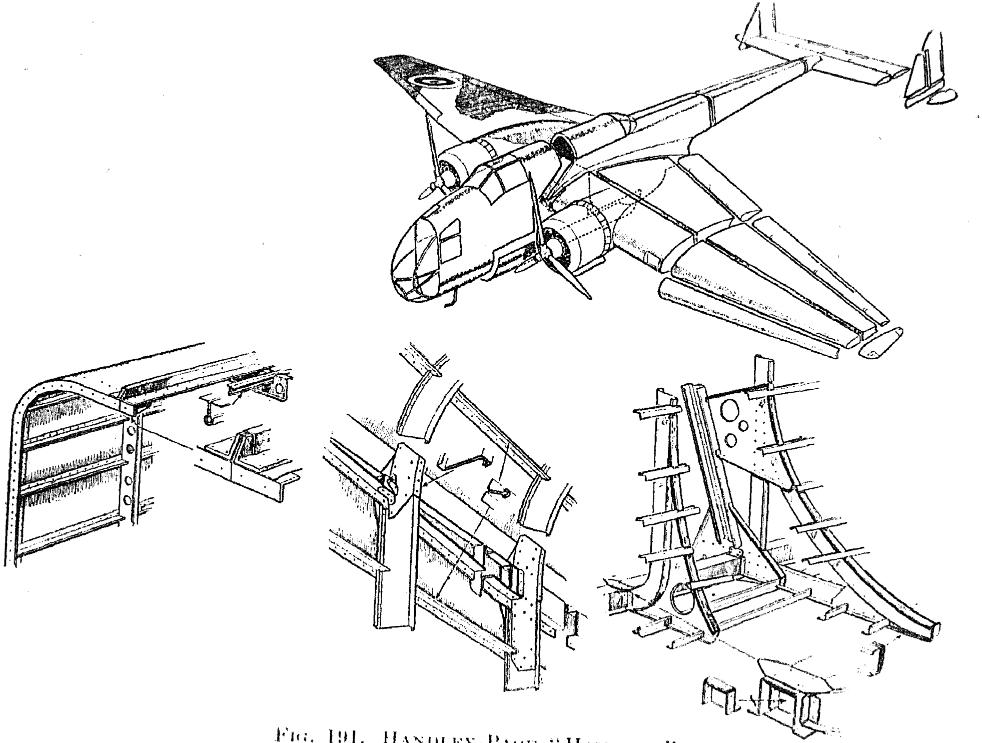


FIG. 191. HANDLEY-PAGE "HAMPDEN"

(*By courtesy of "Flight"*)

Many advantages can be claimed for this method and there do not appear to be any corresponding disadvantages. It is possible to employ many more men on the work at the same time and thus to increase the rate of production. The interior is completely accessible for riveting and for the installation of wiring, hydraulic pipe lines, equipment and so forth. Complete interchangeability is given and the repair of damaged parts is simplified.

As will be seen from Fig. 191, the details of the construction are not unconventional. The metal skin is riveted over an internal structure of transverse frames and longitudinal stringers. The frames are of channel or "Z" section and the stringers are each made up of two drawn strip angles, back to back, to form a "T" section. The edges of the flanges are curled over one into the other.

The centre line joint between the halves of the rear fuselage is shown in the left-hand detail of the illustration. The strip of shell plating next to the joint is left wide and an angle section riveted on the outside. The free edge of the shell is then turned up to lie along the vertical flange of the angle. A "U" section is put over the joint when the halves are brought together and rivets are then put right through the six thicknesses.

American Monocoques. Boeing. The Boeing Aircraft Company have had considerable experience in the design of large aircraft; in fact, they are now concentrating exclusively on these. A very interesting paper presented by three members of the Boeing design staff is quoted below to show some of the problems which they have met.[1]

> "In monocoque fuselage design there are several items of more than passing interest. First, with large airplanes care to obtain adequate torsional rigidity is believed to be essential. In scaling up from smaller models, the tail surfaces frequently increase in moment of inertia faster than the after end of the fuselage increases in size and stiffness. This makes for decreased torsional frequencies, and to maintain reasonable rigidity the fuselage skin thicknesses must often be greater than those required by the dictates of strength alone. Second, body shear stresses tend to become higher in the large airplane. Because of this, care must be taken to provide adequate continuity of all stiffeners, adequate end connections for stiffeners and proper provision for stress concentrations at critical spots. Cut-outs for doors, windows and access must receive their share of study. Tests have shown that a reinforcement around a cut-out consisting of a skin patch and a frame of close section with good ties to the adjacent stiffeners can give all that is required in the way of strength and stiffness. The use of longerons is more or less reminiscent of truss fuselage design in the past, but if used judiciously longerons still can serve the excellent purpose of providing load carry-through ability by large openings and distribute concentrated loadings into the adjacent monocoque structure.
>
> "For the pure reinforced shell fuselage, analysis methods for bending have by this time become a matter of mere routine due to the accumulation of test data over a period of years. The methods simply must take into account the crushing or column characteristics

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[1] "Problems in the Design and Construction of Large Aircraft," by R. J. Minshall, J. K. Ball, and F. P. Laudan, presented to the National Production Meeting of the Society of Automotive Engineers at Los Angeles, October, 1936.

of the stiffeners and the amount of compression skin effective in the application of the beam formula. There is one pleasing characteristic of a fuselage: Its extreme compression stiffeners may fail and the structure still take more load due to the pick-up of adjacent members less distant from the neutral axis. The considerations for shear are not so simple, and the allowances a designer must make should be in keeping with the tension field characteristics of the covering. If high-tension fields are present, these are not to be overlooked, but there is no point in penalizing the stiffeners or riveting unnecessarily by applying extreme Wagner beam (tension field) ideas, the skin purposely made reasonably thick to provide proper stiffness characteristics. Tests have indicated that stiffeners receive load according to the amount of skin wrinkling, paper thin skin providing one loading extreme and thick skin the other. The amount of allowance to be made must at the present time be largely up to the good judgment and experience of the designer."

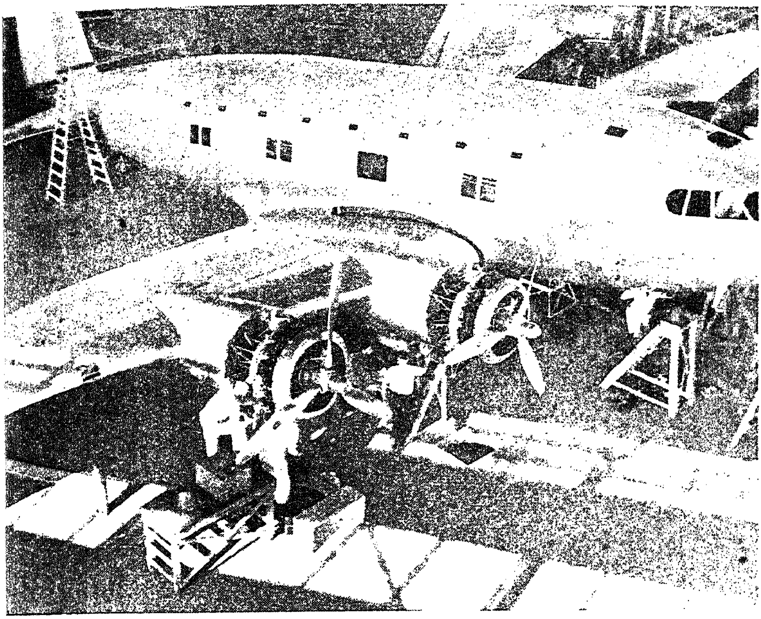


FIG. 192. FINAL ASSEMBLY WORK ON A BOEING 307 STRATOLINER
(*By courtesy of the Boeing Aircraft Company*)

The fuselage of the Boeing 307 Stratoliner is illustrated in Fig. 192. This fuselage is of circular cross-section to stiffen it against the effects of internal pressure when the cabin is supercharged. It will be seen that the skin is laid on in longitudinal strakes and that the panels formed by the transverse rings and longitudinal stiffeners are substantially square in the most heavily loaded centre part of the fuselage.

Consolidated. While the Consolidated Aircraft Corporation is principally known for large flying boats, they are also constructors of small military land planes. The fuselage of the PB2A under construction is shown in Fig. 193.

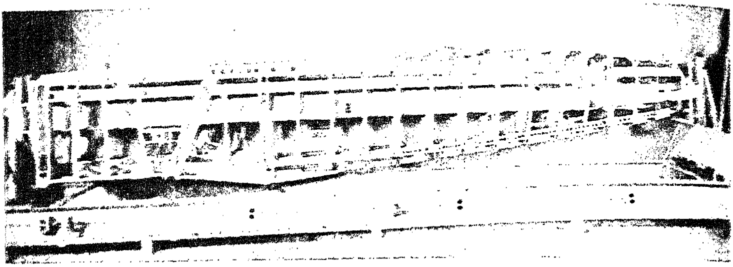


FIG. 193. CONSOLIDATED "PB2A" FUSELAGE FRAMEWORK
(By courtesy of Consolidated Aircraft Corporation)

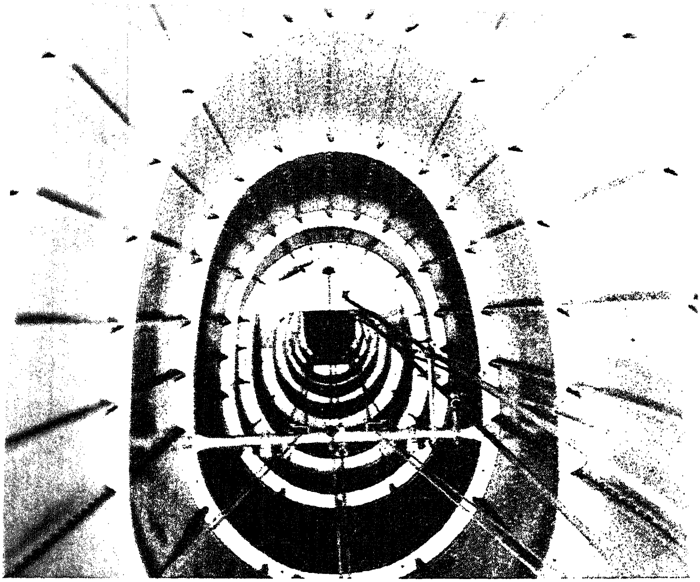


FIG. 194. CURTISS-WRIGHT MODEL 21, INSIDE REAR OF FUSELAGE
(By courtesy of Curtiss-Wright Corporation)

The deep beam passing right through the centre of the fuselage is part of the building jig and not of the fuselage itself. Several points of interest should be noticed. The deep channel section with flanges to the skin provides continuous longitudinal strength along the upper part of the fuselage. Where this is crossed by the transverse rings smaller stiffeners are put into the channel in line with the rings. In addition to these longerons there is also at the top of the fuselage a continuous girder to maintain the strength over the cockpit opening. At its rear end, opposite frame 13, this is tapered off into the skin by a flat strip which passes diagonally to the top of the fuselage across the next four frame spaces. Between the rings this is dimpled. The centre section of the wing which was described and illustrated on page 107 passes continuously across the bottom of the fuselage. Opposite the two main spars are two strong fuselage frames, the front one of which slopes backwards at the rear end of the pilot's cockpit. To the tops of the two spar frames is attached a welded tube crash pylon, the purpose of which is to protect the occupants should the machine overturn in a forced landing. The transverse rings are all of channel section with outward turning flanges riveted to the skin.

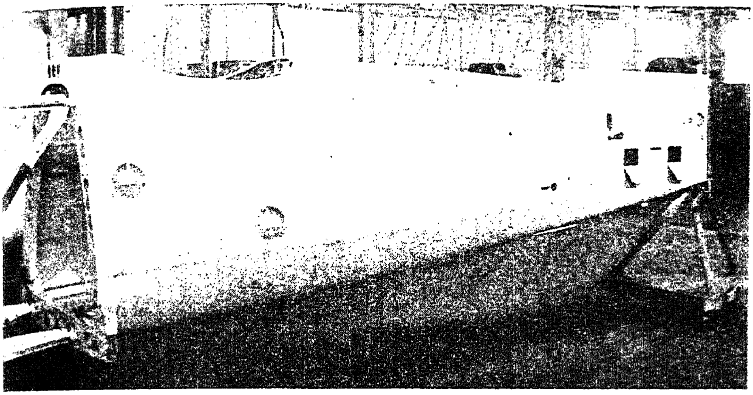


FIG. 195. GLENN L. MARTIN MONOCOQUE FUSELAGE

(By courtesy of the Glenn L. Martin Co.)

Curtiss. The internal structure of the fuselage of the Curtiss-Wright Model 21 is shown in Fig. 194.

This is stiffened with widely spaced transverse rings of channel section pressed from flat sheet. They are notched to allow the more closely spaced longitudinal stiffeners to run through in unbroken lengths. At the top and bottom of the structure, where the stress concentration is higher, the stiffeners are more closely spaced. These should be compared with the Bristol 143 fuselage shown in Fig. 184, where the smaller radius of the fuselage cross-section at the top and bottom was thought to provide sufficient additional stiffness against buckling to remove the necessity for stringers. The stringers of the Curtiss 21 are extruded bulb-angle sections.

Glenn L. Martin. The monocoque fuselage is becoming increasingly popular in the U.S.A., where its use has largely superseded the welded tubular fuselage at one time so favoured. A typical example from the Glenn L. Martin Company is illustrated in Figs. 195 and 196. The aluminium alloy skin is laid on flat to an internal framework. No corrugations are used, but the shell is well supported against buckling. The internal structure consists of hoops, which give the fuselage its transverse shape. These hoops are pressed from aluminium alloy sheet in the form of channels with flanged lightening holes. There are four main continuous longitudinal members from the front bulkhead to the tail with a number of smaller intermediate longitudinals. These are closely spaced at the top and bottom where the bending stresses, due to the vertical load on the tail, are greatest. All the stiffeners are in the form

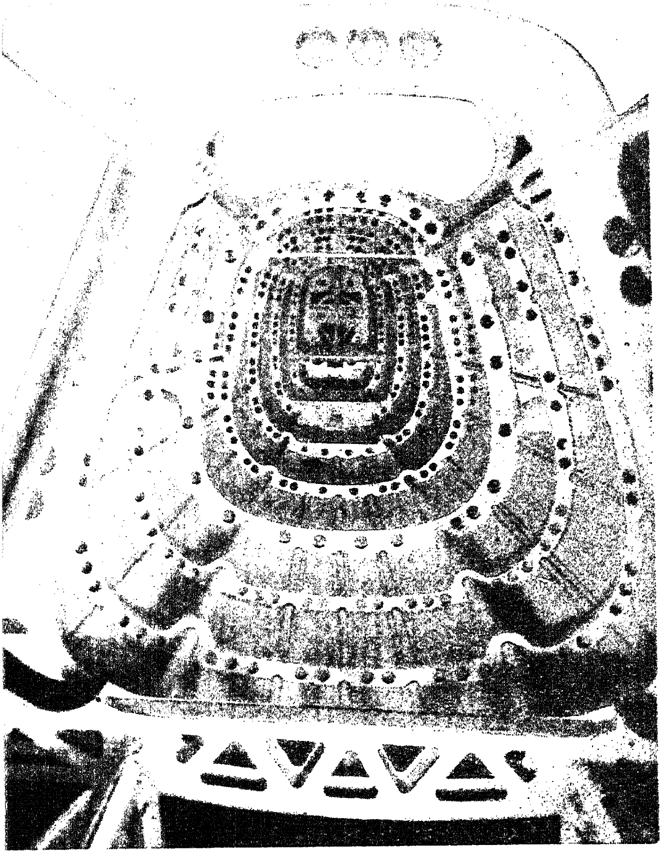


Fig. 106. Glenn L. Martin Monocoque Fuselage—Internal Structure

(By courtesy of the Glenn L. Martin Co.)

of deep or shallow channels, round-backed, with two flanges riveted to the shell. It is, of course, necessary to have cockpit openings in a fuselage of this kind, and it will be seen that in the shape of the opening there are no sharp corners and that the edge is beaded with a wide stiffening flange right round. The continuity of strength is preserved by the heavier longitudinal stiffeners, already mentioned, which run the length of the machine close to the cockpit opening on each side. The material is aluminium alloy, 24S, which is similar to duralumin but of slightly higher physical properties.

Northrop. The wing construction of the Northrop 2E bomber was described on page 115. It was shown that the loads were widely distributed and that there were no concentrations of stress. The fuselage is built on to the top of the wing, which runs through unbroken. Opposite to each of the main plane spars a ring frame is built up in the fuselage and well bracketed to the spar. These frames are of channel or Z-section, whilst in the rear end of the fuselage rounded Z-section frames are used (see Fig. 197).

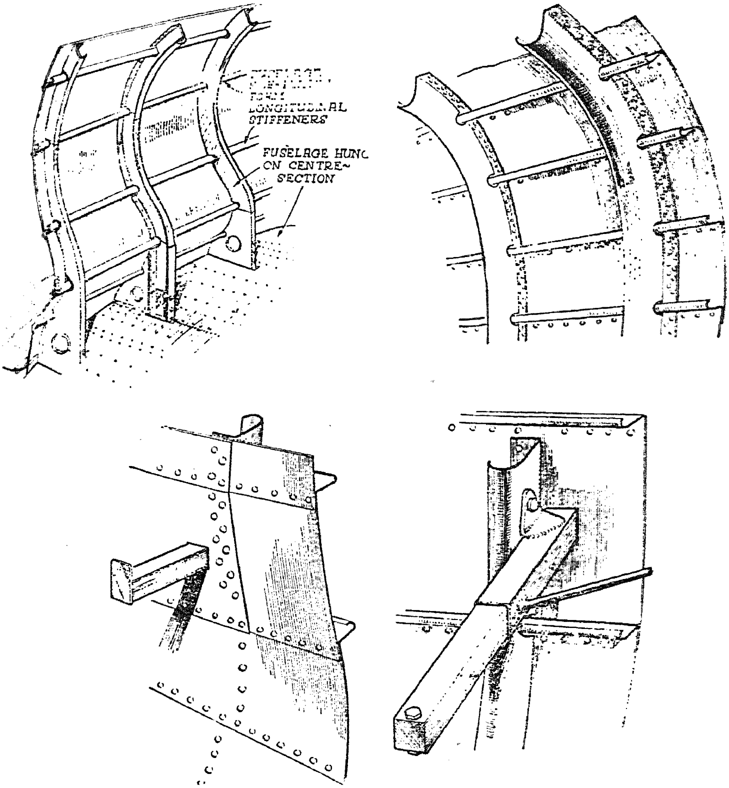


FIG. 197. DETAILS OF NORTHROP FUSELAGE
(By courtesy of "Flight" and "The Aeroplane")

No separate stringers are used, but the plating is put on in narrow strips, one edge of each being flanged inwards to form a longitudinal stiffener. The frames are notched to allow the stiffeners to pass through.

A simple form of retractable step gives access to the fuselage. This is shown in Fig. 197 and consists of a square sectioned step which slides in a square tube bolted inside to one of the frames.

Vultee. The fuselage of the Vultee V.11 is of semi-monocoque construction. It differs from conventional practice in that there are no longitudinal stringers (see Fig. 198).

The aluminium alloy rings and bulkheads are forged in the drop hammer and these are covered with plain aluminium alloy sheet riveted on. The cockpit openings are reinforced by formed longerons to carry the concentrated loads occurring at these points, and round the door is a formed aluminium alloy frame (see Fig. 199), which provides a strong local reinforcement. The construction of one of the main bulkheads to which the centre section is attached is shown in Fig. 200, from which it will be seen that the main loads are carried down the whole bulkhead. The use made of forgings is also clear and is consistent with the wing construction (see page 118).

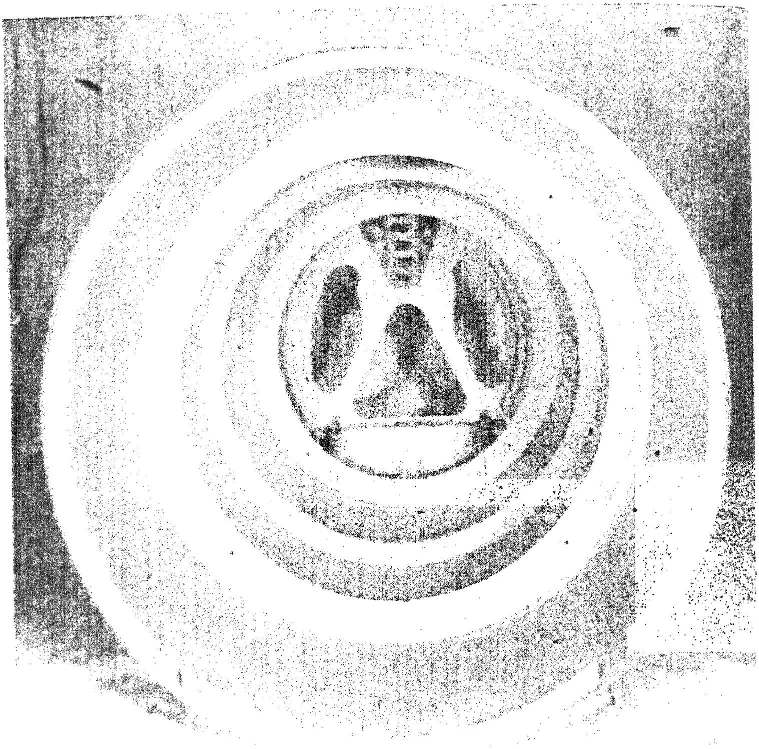


FIG. 198. VULTEE "V-11" MONOCOQUE

(*By courtesy of Vultee Aircraft*)

On the bottom of the fuselage are two fore-and-aft vertical bulkheads to which the lower surface of the wings is attached. These form runners on which the aeroplane can slide should it make a forced landing with the undercarriage up (see Fig. 201).

Czechoslovakian Monocoques. Avia. The fuselage of the Avia 51 high wing monoplane is of "mixed monocoque" construction. There are six

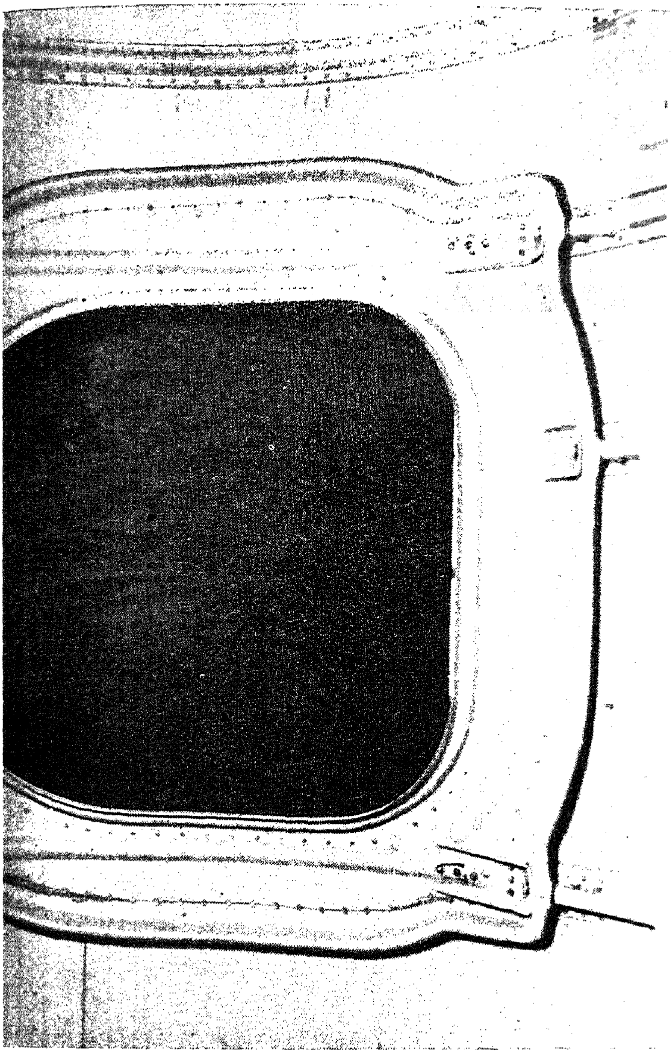


FIG. 199. VULTEE "V-11" COCKPIT OPENING
(*By courtesy of Vultee Aircraft*)

main stringers or longerons of Ω sections. At the forward end, four of these coincide with the four main engine mounting attachments. The two upper longerons run beside the wing attachment fittings and the lower ones beside the undercarriage fittings, thus spreading the concentrated loads at these points fore and aft. In between the main longerons are lighter channel stringers which are broken at the bulkheads, of which there are seven. Fig. 202 shows three of these bulkheads, one at the engine mounting and the others opposite to the front and rear spars respectively. The wing attachment fittings mentioned above and on page 124 can be clearly seen.

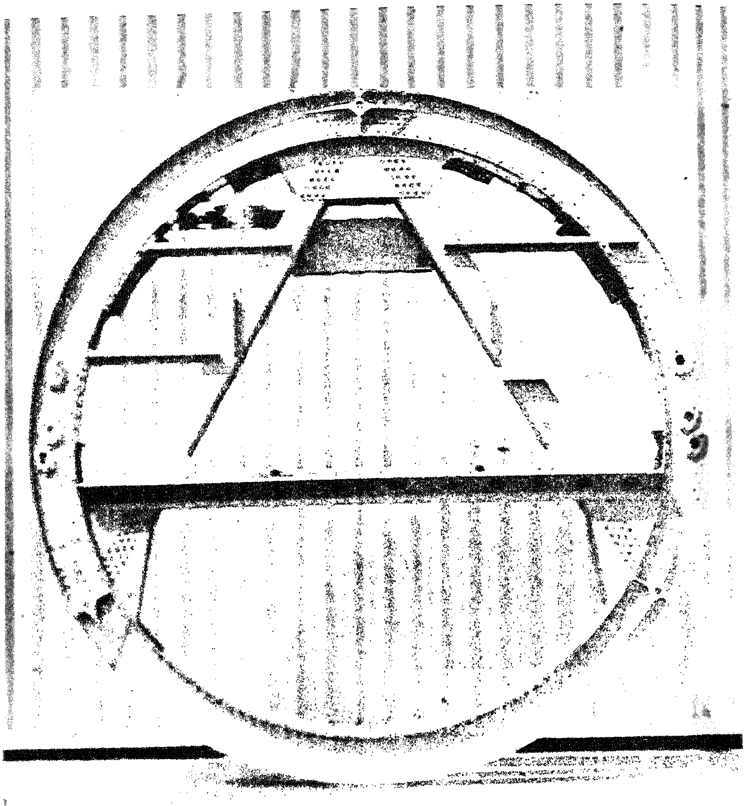


Fig. 200. Vultee "V-11" Main Fuselage Bulkhead

(By courtesy of Vultee Aircraft)

Between the main bulkheads are Z-section hoops mounted on the inside of the stringers, and not in contact with the shell plating. This plating is applied in longitudinal strakes and riveted to both stringers and bulkheads.

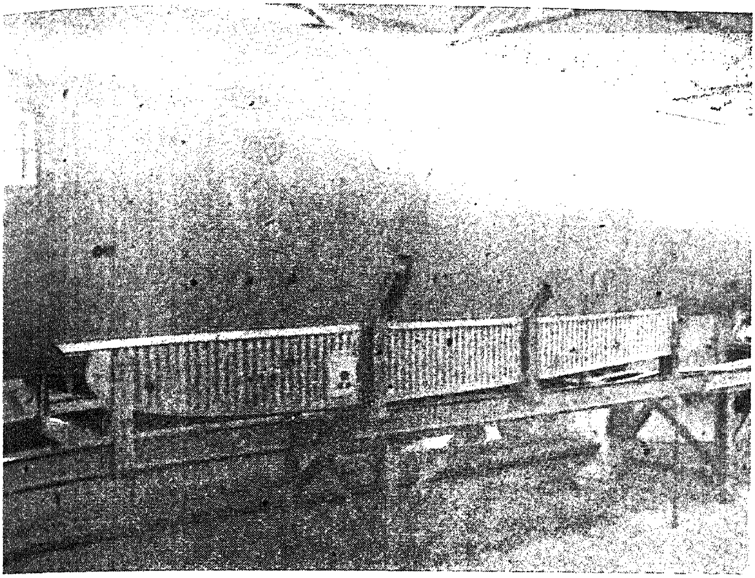


FIG. 201. VULTEE "V-11" WING JOINT ON FUSELAGE
(*By courtesy of Vultee Aircraft*)

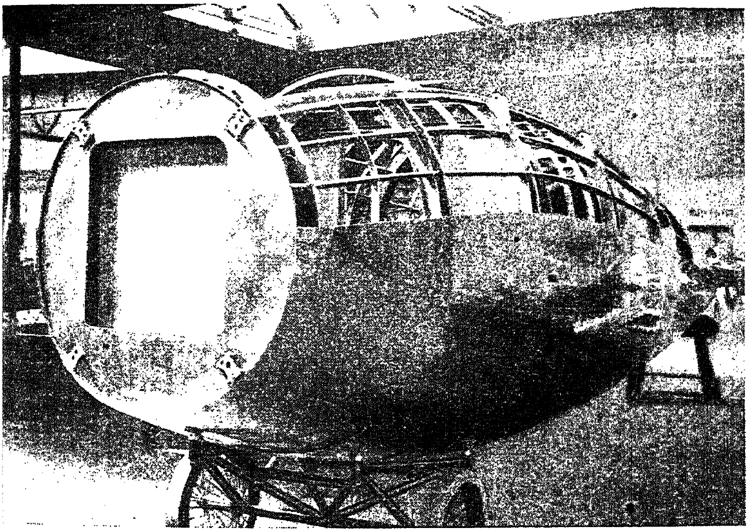


FIG. 202. AVIA 51 MONOCOQUE FUSELAGE
(*By courtesy of Avia*)

French Monocoques. S.N.C.A. du Midi. The fuselage of the Dewoitine D.33 "Trait d'Union" is shown in Figs. 203 and 204. This machine is an excellent example of this firm's construction. It has a monocoque with duralumin skin riveted on in thin flat sheets. The internal structure consists of deep frames which change the section of the fuselage gradually from a rectangle in the cabin to a narrow ellipse at the stern. Shallow stringers run continuously from end to end and are slotted into the frames.

The fuselage is broken at the main plane spar, which runs right across. The leading edge is also carried through the fuselage, and there are five bolted connections on each side, which can be clearly seen in the illustration. (Fig. 203.)

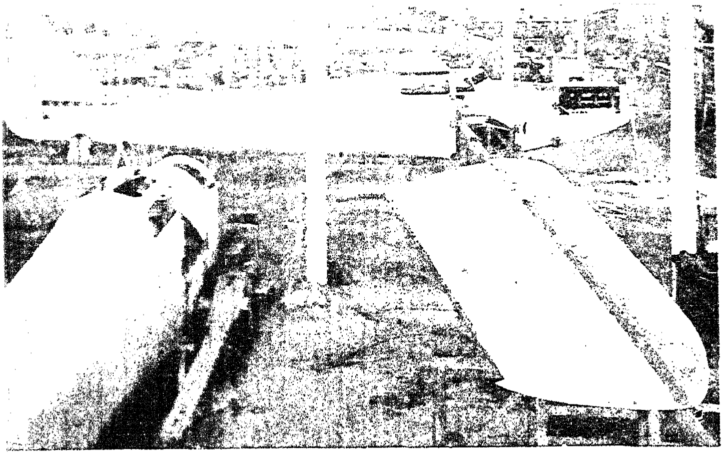


FIG. 203. DEWOITINE D.33 DURING CONSTRUCTION

(By courtesy of the Société Aéronautique Française)

S.N.C.A. du Nord. The Potez 63 twin-engine three-seat monoplane has been built for the French Armée de l'Air in large numbers. The wing structure was described on page 128.

The centre section of the wing is built up into one unit with the centre part of the fuselage. The tail end and the cockpit portions of the fuselage are built separately and attached to the centre unit in the final assembly stage of the construction.

A portion of the centre fuselage is shown in Fig. 205 and a joint between a transverse frame and a stringer in Fig. 206.

The structure is a straightforward and orthodox monocoque. The transverse frames are of Z-section and the stringers of angle section, the latter being continuous and carried through notches in the frames. At each joint a small angle piece connects the two.

The method of providing a gunner's cockpit is shown in Fig. 205. A double angle passes round the edge of the opening to stiffen it and to carry the panel stresses round the gap.

At the end of each portion of the fuselage is fitted a strong right angle frame, to which is attached the stringers and the skin. On assembly the end frames of each section are bolted together as shown in Fig. 207.

The bolts are closely spaced and strong brackets are fitted at the main stringer points.

In most places where the skin is attached to main duralumin members a double row of staggered riveting is used.

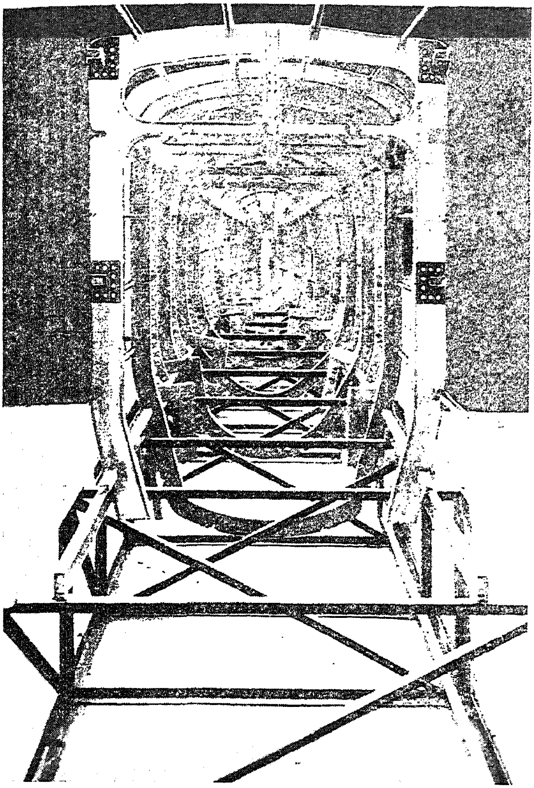


Fig. 204. Dewoitine D.33—Fuselage Structure

(By courtesy of the Société Aéronautique Française)

S.N.C.A. de l'Ouest. The wing structure of the Loire-Nieuport 161 was described and illustrated on pages 130 and 131.

The fuselage is a monocoque and the skin covering is laid on in narrow strips. Although this increases the amount of riveting it saves panel beating since such strips require only curving to the cross-section and will easily take the slight fore-and-aft curvature. Continuous longitudinal stringers run through all but the main transverse frames. These stringers are of closed channel section, the outward turning flanges being riveted to the skin. The transverse frames are built up of flat sheet with double flanges, one to the skin and the other supporting the inner edge of the web. The lighter intermediate ones are pressed in Z-section and are notched to allow the stringers to pass through (see Fig. 208).

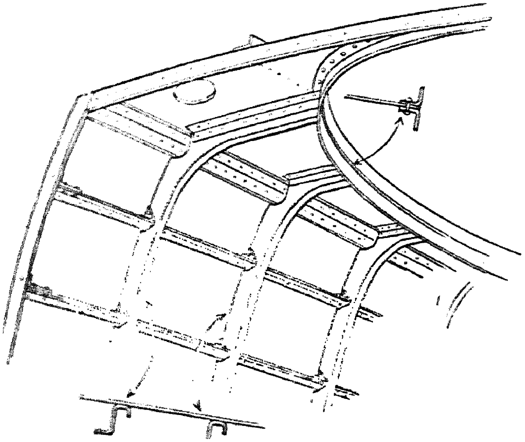
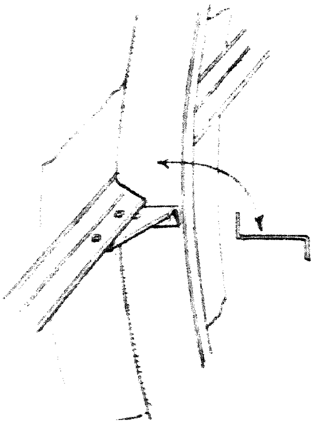


Fig. 205



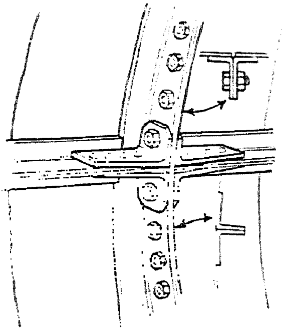


Fig. 206

Fig. 207

Figs. 205–207. Potez "63" Fuselage Details

(*By courtesy of "Aircraft Production"*)

S.N.C.A. du Sud Est. One of the principal products of the S.N.C.A. du Sud Est is the LeO 45 high-speed bomber.

The fuselage is of oval cross-section and has sixteen bulkheads together with numerous intermediate light frames. Two typical bulkheads are shown in Fig. 209.

The bulkhead on the left is a heavy one situated opposite one of the main plane spars. A description and illustration of the wing root fittings has appeared on page 130. These key on to the forgings which protrude through the fuselage sides. The forgings are carried right across the fuselage in channel section and thus the end loads balance out without imposing any stress in the fuselage structure itself. These channel sections are sandwiched in between the two sides of the bulkhead, which are of flat sheet, well stiffened with internal channels. The stringers pass unbroken through notches in the bulkheads, but a continuous angle runs round inside the stringers.

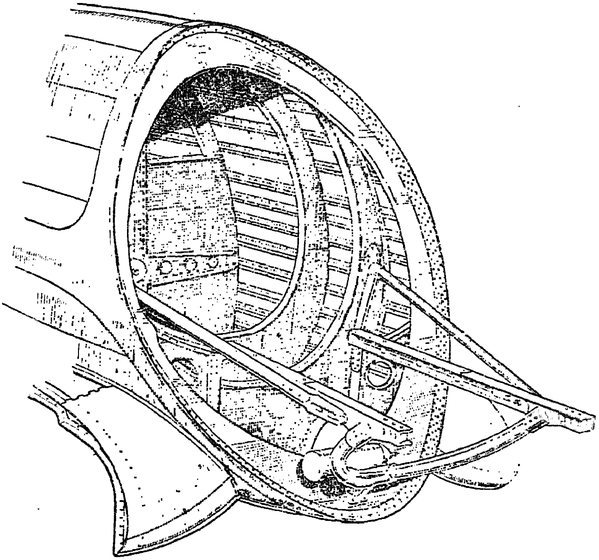
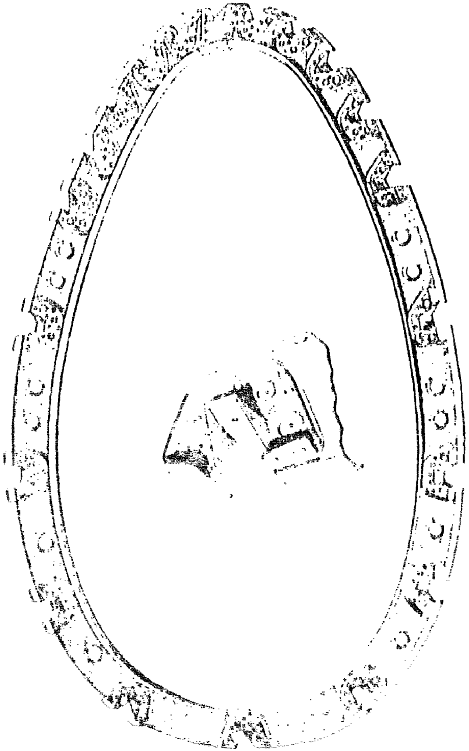
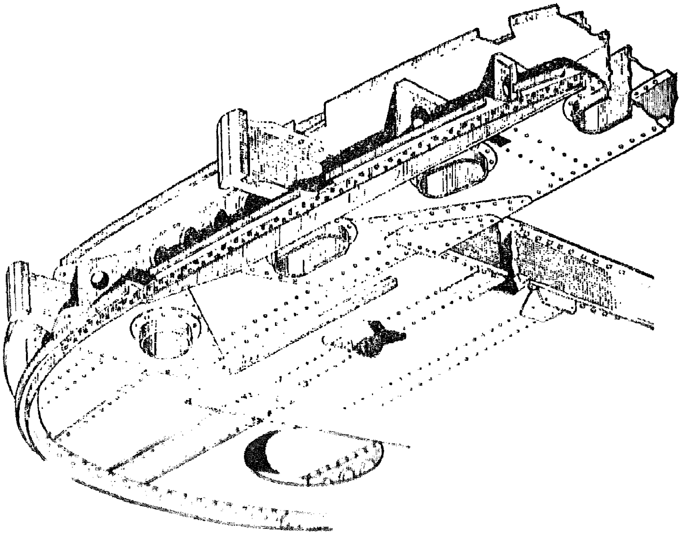


Fig. 208. Loire-Nieuport "161" Front Fuselage and Engine Mounting

(*By courtesy of L'Aéronautique*)

One of the lighter bulkheads of the rear end is shown on the right of Fig. 209. This is pressed up in halves, port and starboard, out of flat dural sheet. It is of Z-section and slotted to allow for the stringers. Where each stringer passes through, a special pressing is riveted on. This helps to make good the break in the strength of the transverse member, and also anchors the stringer both to the skin and to the frame. Theoretically it may not be necessary to anchor these together since the load is transferred by way of the skin. It is undoubtedly, however, a great help in assembly and makes a more robust framework to which the skin can be riveted. A section of the fuselage showing both light transverse frames and a heavy main spar bulkhead is illustrated in Fig. 210.





Kellner-Béchereau. A perfect example of the monocoque is shown in Fig. 211. This is the Kellner-Béchereau fuselage. There are no longerons, and the load is carried entirely in the duralumin skin. A method of construction has been devised which is extremely simple and removes most of the difficulties of building a fuselage of this kind. A wooden mould is made to the shape of the fuselage. Its surface is recessed with the steel-faced grooves to take the extruded T-section and flat strip stiffeners which support the shell. These are cut to length and inserted in their appropriate grooves. The shell is made of trapezoidal plates bent to single curvature. These plates are laid on the mould with lapping edges in their appropriate positions and held with leather straps passing right round. The rivet holes are drilled from the outside (Fig. 212). The work is then dis-assembled and re-erected for riveting together. An extremely light structure results from this method, whereby all superfluous and secondary structure is ruthlessly eliminated.

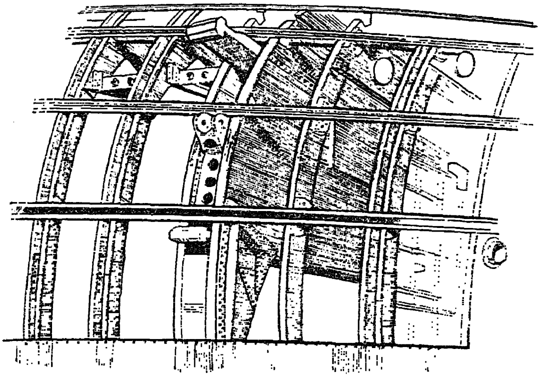


FIG. 210. LEO "45" WING JOINT ON FUSELAGE
(*By courtesy of L'Aéronautique*)

German Monocoques.[1] One of the pioneers of the metal-clad structure was Professor Hugo Junkers, in Germany, whose work is referred to specifically on a later page. It developed continuously from his earliest conception to its present form. Other German constructors started many years later and their ideas show remarkable conformity.

Henschel, Heinkel, and Messerschmitt have now produced single- and twin-engined military aircraft having smooth metal-skinned fuselages. Dornier, whose early work on all-metal flying boats was mentioned on page 3, now builds land planes also, with fuselages entirely in the modern fashion.

Whatever a constructor may have to do in the nose and centre section of a fuselage to suit wing structure and cockpit requirements, it is to the rear end that one looks for his basic design. The external and internal limitations imposed on his work are less here and he has only to produce a clean aerodynamic form of sufficient strength to carry the tail loads.

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[1] At the time this edition was being prepared it was difficult, owing to the political situation, to obtain adequate particulars of new German aircraft.

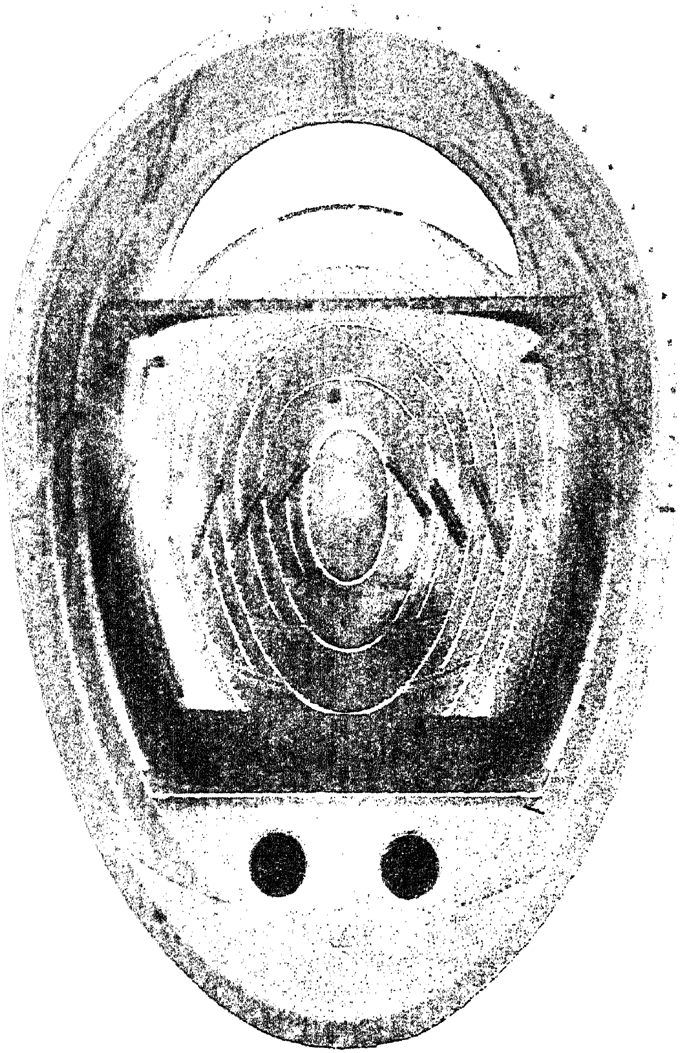


FIG. 211. KELLNER-BÉCHEREAU FUSELAGE

(*By courtesy of Kellner-Béchereau*)

In the work of all these constructors one finds a smooth metal-clad structure of elliptical cross-section tapering to the tail unit. It is flush-riveted and lap joints in the skin are usually joggled to give a flat finish. In the Messerschmitt Me.109 the transverse laps were so arranged that the external edge of the lap pointed forwards, but it was carefully filled.

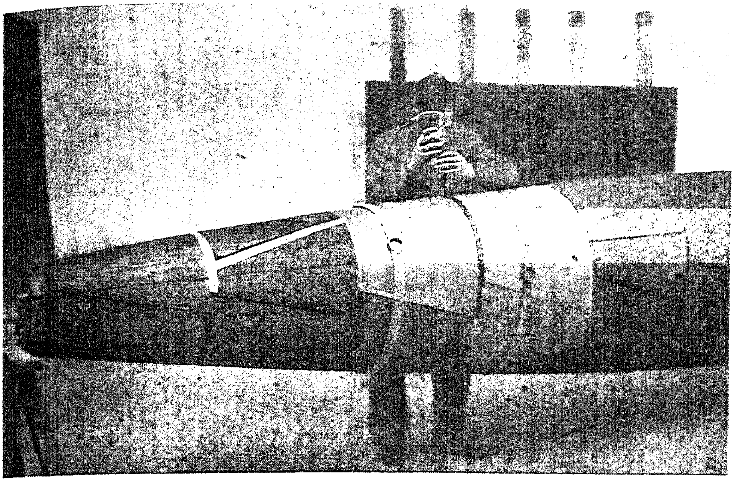


FIG. 212. KELLNER-BÉCHEREAU FUSELAGE—BUILDING JIG
(By courtesy of Kellner-Béchereau)

The internal structure consists of transverse rings, across the face of which run the longitudinal stringers to which the skin is riveted. In the Dornier Do.215, the Heinkel He.111 and 112, and the Messerschmitt Me.109, these rings are of Z-section, while the stringers are of square "top hat" section. In the Dornier, the two outstanding flanges are riveted to the skin (Fig. 214), but in the others greater economy in riveting is achieved at the expense of structural efficiency by reversing the section so that only the centre web is riveted to the skin (see Fig. 213).

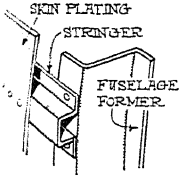


FIG. 213
(By courtesy of "The Aeroplane")

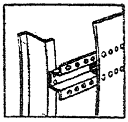


FIG. 214
By courtesy of "The Aeroplane")

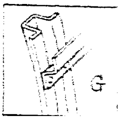


FIG. 215
(By courtesy of "The Aeroplane")

Their positions are changed round in the Henschel Hs.126, in that the transverse rings are of "top hat" section and the stringers of Z-section (see Fig. 215).

In all these examples the main structural material appears to be a light aluminium alloy of the type of duralumin.

Junkers. Junkers initiated and used for many years a particular form of metal construction, the outstanding feature of which was the corrugated duralumin covering. A typical example of this is shown in Fig. 216.

They have now, however, turned over to a smooth covering as illustrated in Figs. 217 and 218, the fuselage of the Junkers JU.160.

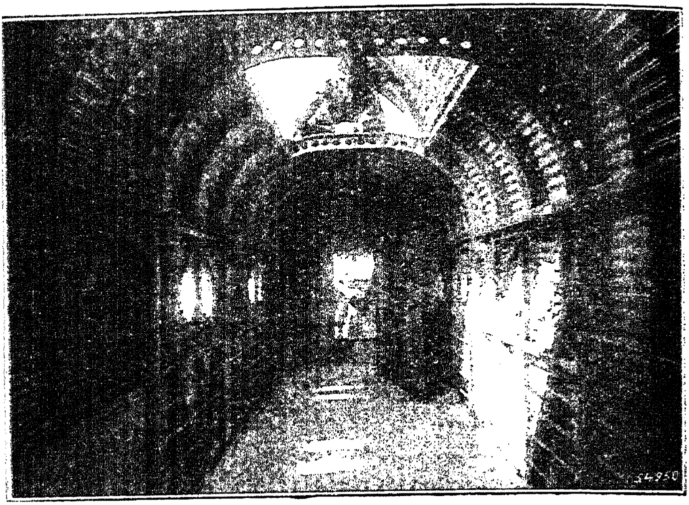


FIG. 216. INTERIOR OF FUSELAGE OF JUNKERS JU.52
(*By courtesy of Junkers-Werke*)

Four main longerons run the full length. These are of U section, open to the inside of the fuselage. To prevent deformation of the open edges of the longerons, small bridge pieces are riveted across at intervals. In between the longerons at intervals of about a foot are spaced smaller stringers, also continuous, except where interrupted by windows and the doorway. The stringers are of flanged U section but unlike the longerons, the flanges are riveted to the skin. The transverse shape is maintained by six main bulkheads and numerous intermediate rings of Z section. Two of the bulkheads coincide with the two main spars of the wing, the centre section of which is built in with the fuselage.

A comparison with the older type of fuselage with corrugated skin shows the newer form to have a more complex internal structure, the skin being divided into much smaller panels. The change to an elliptical cross section is also noticeable.

Italian Monocoques. Breda. The Breda 32 fuselage is entirely metal-covered, the skin having the characteristic Breda ribbing to stiffen it. The internal framework, on which this metal skin is laid, forms, in itself, a braced structure of channel sections. The skin might therefore be considered redundant structurally, yet it relieves the

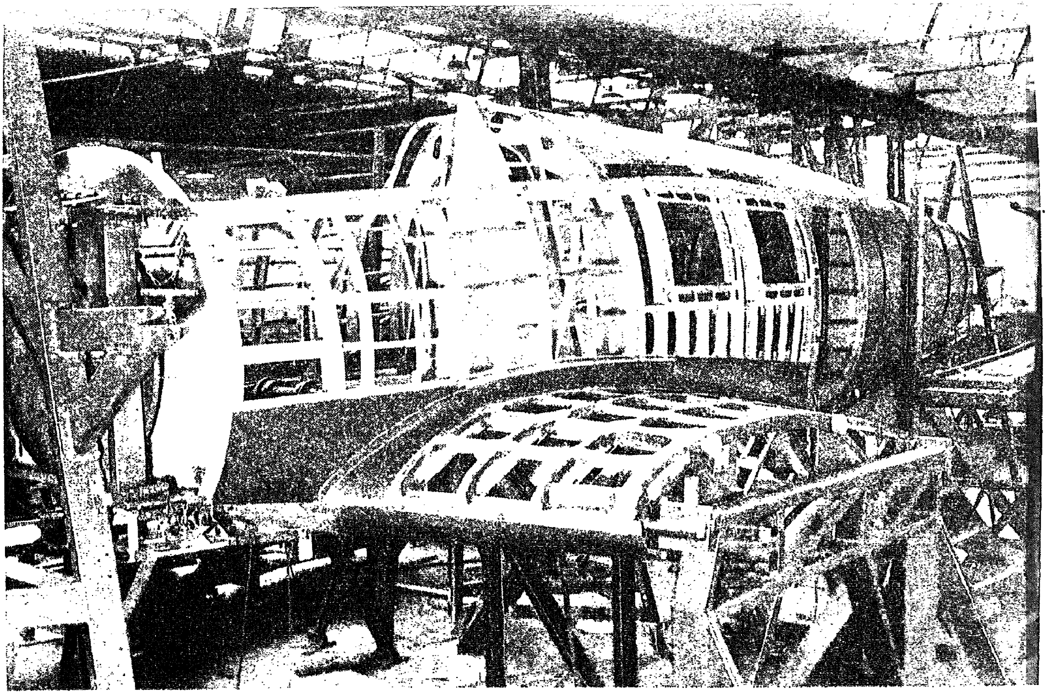


FIG. 217. JUNKERS JU.160 FUSELAGE
(*By courtesy of Junkers-Flugzeugwerk A.-G.*)

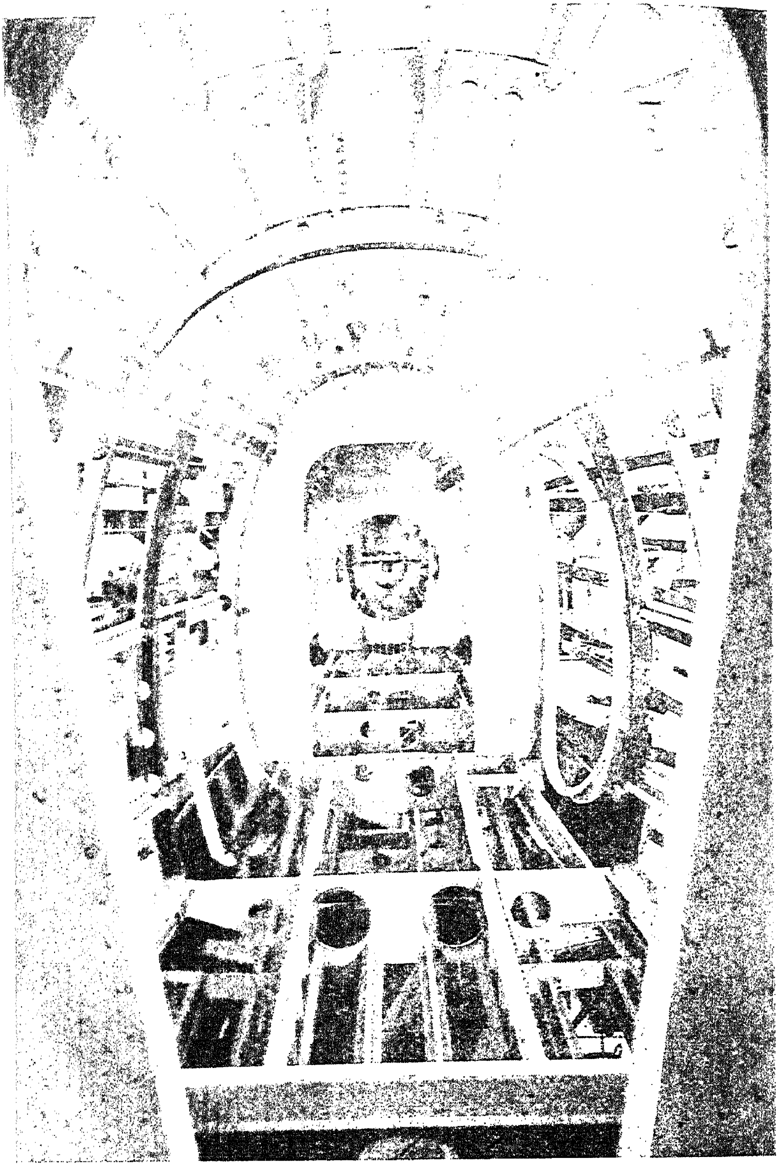


FIG. 218. JUNKERS JU.160. INTERIOR OF FUSELAGE

(By courtesy of Junkers-Flugzeugwerk A.-G.)

framework of stress and allows this to be of a lighter construction. Further, it is much more permanent than fabric covering, serviceable under adverse and variable weather conditions, besides being considerably more robust. (Figs. 219 and 220.)

Fiat. The fuselage of the Fiat G.2. is a metal box of duralumin, not unlike the Short *Valetta* described on p. 159. The conception is not quite that of a monocoque, since there is a substantial framework inside. This consists of closely-spaced frames of duralumin with continuous longitudinal stringers of smaller depth passing across at right angles. The frames are well lightened with flanged holes, and, at points of high loading, such as occur at the main plane attachments, they are made much more robust. The frames which correspond to the front and rear spars are built up in box form and have small diaphragms at intervals. Immediately behind the rear spar on the starboard side, is the entrance door to the cabin which is reached by stepping on the trailing edge of the centre section. The corners of the door opening have large radii supported by channel stiffeners. This counteracts the tendency of a crack developing where there is a sudden change of section and is very sound practice. (Figs. 221–2.)

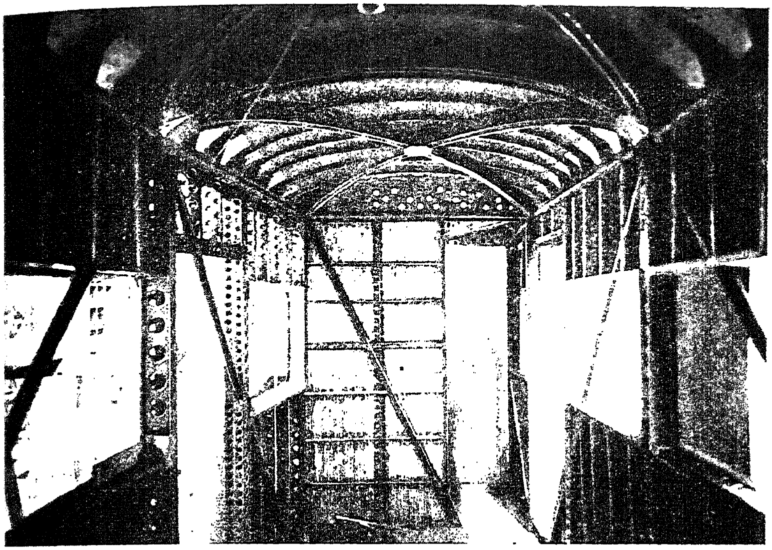


FIG. 219. BREDA 32. FUSELAGE INTERIOR

(By courtesy of Società Italiana Ernesto Breda)

A later Fiat machine, the G.18 V, has a very similar fuselage structure to the G.2. The only noticeable differences are that the multiplicity of lightening holes in the transverse frames is avoided, and that the upper portions of the frames are pressed in one piece instead of being joined at the corners by the triangular brackets shown in Fig. 221.

The Material of the Monocoque. The fuselages here considered have been of aluminium alloy sheet, which, by reason of its better mass strength ratio, is more suitable than any available grade of steel. Sheet steel, even when corrugated, may be quite unstable in the large unsupported panels, and its weight prohibits the use of thicker gauges or closer spacing of framework.

The sections in the supporting structure are mostly drawn or rolled, though extruded sections are now being widely used.

Magnesium alloy may eventually prove the best material for monocoque construction. If its cost can be reduced and the corrosion

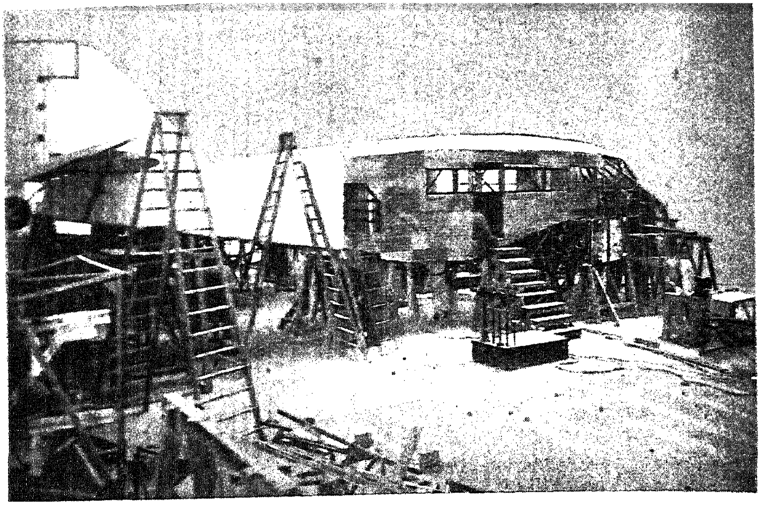


FIG. 220. BREDA 32. FUSELAGE UNDER CONSTRUCTION

(*By courtesy of Società Italiana Ernesto Breda*)

difficulty solved, it would alter the whole conception of fuselage design and allow a pure shell to be built without any substantial internal structure.

BRACED STRUCTURE FUSELAGES

The braced fuselage in its various forms is still a very popular type of structure. It is developed in several different ways, which may be classified into—

1. Tubular steel structure with welded joints.
2. Tubular structure with mechanical joints.
3. Drawn strip structure.

The essential idea in all these groups is that the fuselage is a beam consisting of four corner members or longerons braced either by struts and wires or by struts and tubular tie members. The whole is covered with fabric to act as fairing and to protect the occupants from wind and weather.

1. Tubular Steel Structure with Welded Joints. Mention of the welded fuselage at once brings to mind the name of Anthony Fokker, since he more than anyone was responsible for making it so important a method.

There has been great prejudice against welding, particularly in

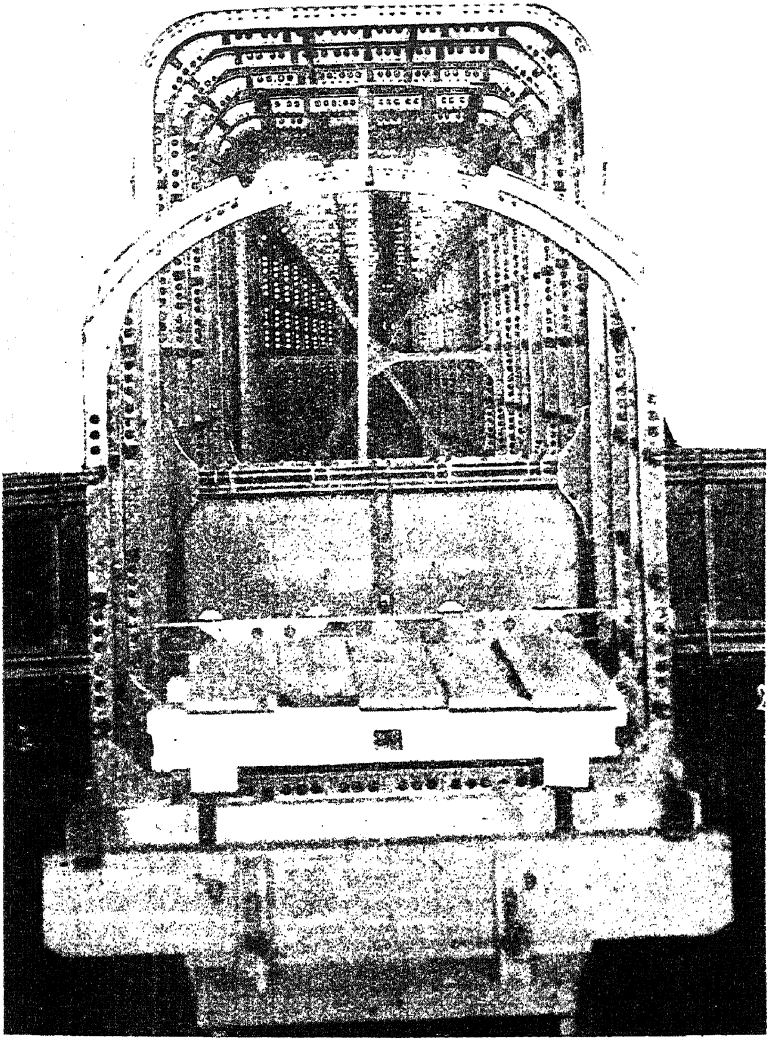
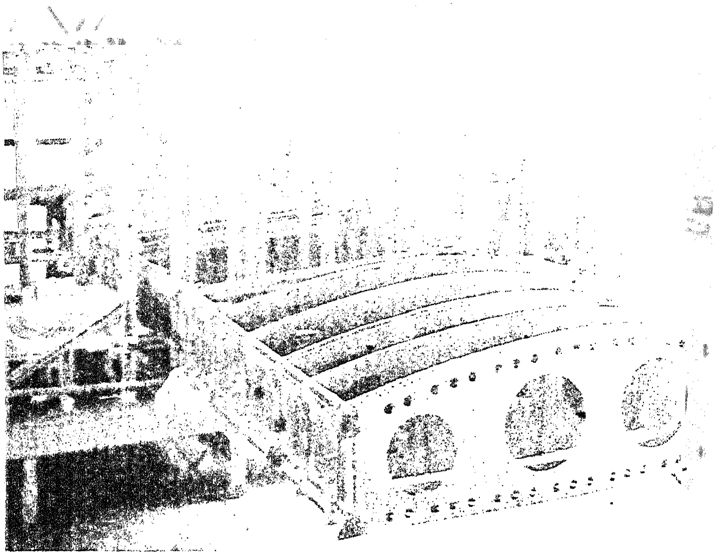


FIG. 221. FIAT G.2. FUSELAGE, INTERNAL FRAMING

(By courtesy of Aeronautica d'Italia)

England and France. But the trouble-free record of Fokker aircraft throughout the world and the extremely small cost of their maintenance gradually broke down that feeling. Even so, most of the British examples of welded construction show complications added as



222. Fiat G.2. Fuselage and Central Section
(By courtesy of *Aeronautica d'Italia*)

safeguards, thereby expressing the doubts which are still in the minds of both our Air Ministry and designers. In America, on the other hand, this type was accepted wholeheartedly, and many of the craft built there are frankly copied from Fokker practice.

This method will, therefore, be described first, followed by certain variations [illegible] which have been used in England. Its most striking feature is simplicity and ease of modification. The total plant required is a blow lamp for oxy-acetylene welding, a pair of metal clippers, and a simple jig, multiplied up in proportion to the rate of production. To this must be added experience of what is good or bad welding, and how much distortion may be expected at each point.

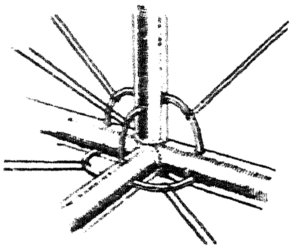


Fig. 223
(By courtesy of "Flight")

As far as possible, the longerons run in unbroken lengths from end to end of the fuselage. Limitations of tube size will probably mean the introduction of several joints in the length of the machine. At these points, even though the tube may change its diameter from, say, 1⅛ in. to 1 in., the ends are merely butted together and welded round. Such butts are placed at nodal points in the structure.

The first stage is the making-up of the longerons. The next is the putting together of the two side panels. The longerons are put down in a simple jig, in which are also placed the vertical and diagonal strut tubes, whose ends are hand-sheared or milled to shape. A small clearance is allowed between these tubes and the longerons. As they now lie in the jig they are tack-welded together. The side panel is then removed from the jig and the joints welded up. The two sides are next erected in their correct positions relative to one another and the horizontal cross tubes added, being first tack-welded. The small corner hoops for taking the bracing wires are put in and each joint completed in all directions.

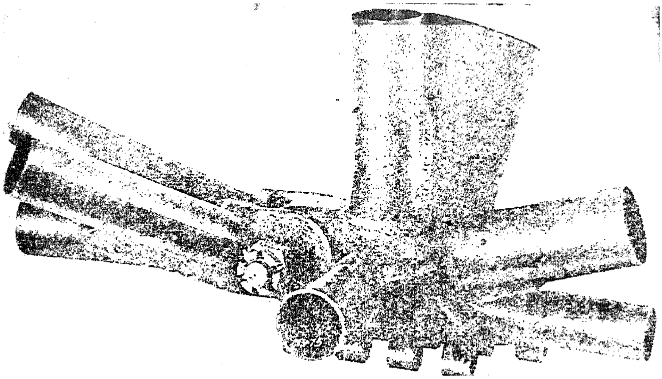


Fig. 224. Fokker Fuselage Joint showing Combination of Tube, Plate, and Machined Bar Work

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

A typical joint from Fokker practice is seen in Fig. 223.

The much more complicated joint in Fig. 224 requires considerable ingenuity and experience to be satisfactory. Some of its outstanding features will be noticed. The tubes are simply butt-welded to each other and to a plate structure, whatever the nature of the load, whether it be tension or compression. In the corner of the V where two tubes meet at an acute angle the welding is thick, being much lighter down the sides of the join. A heavy machined fitting is also welded into the joint, a practice which might be thought to cause considerable distortion, particularly as the tubes are for the greater part 1 mm. (20 s.w.g.) in thickness.

The method is to use two blow-lamps, one of them playing on the mass of metal in the fitting and keeping it hot. If this were not done the temperature of the relatively big mass of the fitting would remain too low and the result would be faulty. The fittings in joints of this kind are held in their correct relative positions by jigs during the tack-welding. In finishing the weld they are left free to expand and contract. It is inevitable that some distortion should take place in the structure. Some of it may be forestalled by making the correct allowances beforehand. At certain points the fittings may be so designed that the final erection holes can be drilled *in situ* after welding. And wherever possible the design should be such that fine limits on hole positions and

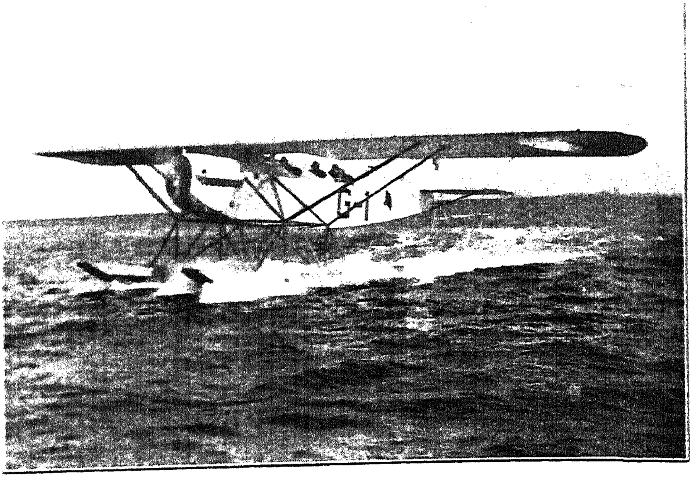


FIG. 225. FOKKER C VIII-W THREE-SEAT RECONNAISSANCE SEAPLANE WITH WELDED STEEL TUBE FUSELAGE
(*By courtesy of N. V. Nederlandsche Vliegtuigenfabriek*)

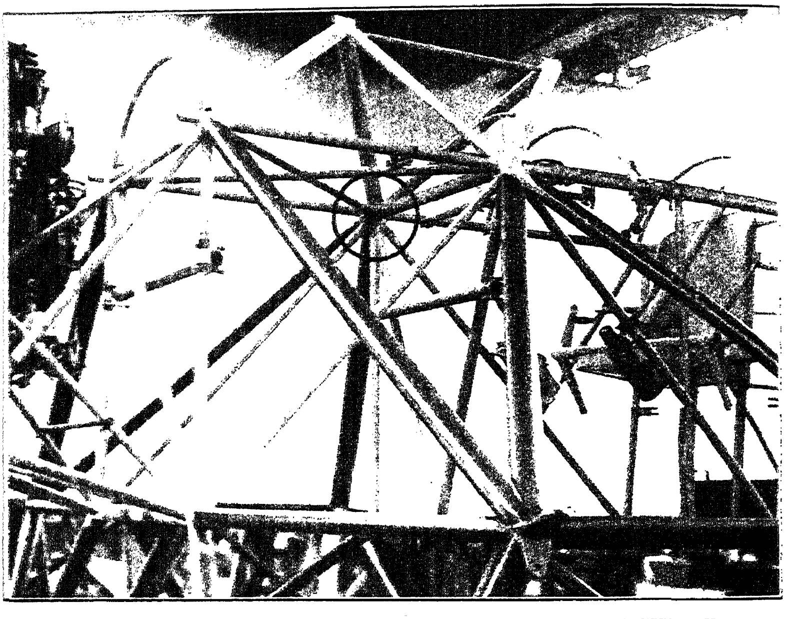


FIG. 226. WELDED STEEL TUBE FUSELAGE, FOKKER C VIII-W
(*By courtesy of N. V. Nederlandsche Vliegtuigenfabriek*)

location points are not necessary. An examination of Figs. 226 and 227 will make clear many of the points in the foregoing text. The particular joint here shown in detail would be next to impossible by any other method than welding. It calls for little in the way of plant and equipment for its construction, but considerable experience is, of course, necessary in its design and manufacture.

The choice of steel is of first importance in the design of autogenously welded structures. Since a complete fuselage is too bulky an object to be normalized on completion, the material must be one which does not harden up and becomes brittle after the heat of welding. This implies a low-carbon steel. That used by Fokker is of approximately the following composition—

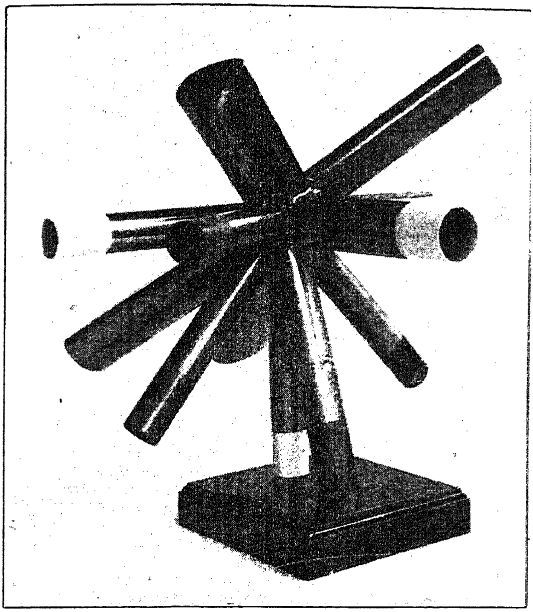


FIG. 227. DETAIL OF FUSELAGE JOINT, FOKKER C VIII-W

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

Carbon	0·09–0·13 per cent.[1]
Manganese	0·45–0·6 per cent.
Silicon	0·1–0·15 per cent.
Phosphorus	<0·05 per cent.
Sulphur	<0·05 per cent.

Its physical properties are—

Tensile Strength . . .	>28·6 tons/sq. in.	as supplied cold rolled
Yield Point	>25·5 tons/sq. in.	

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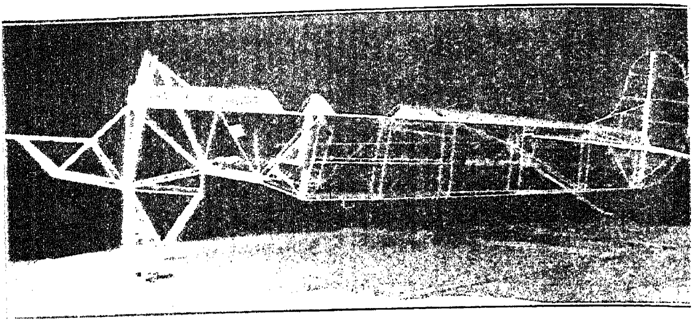
[1] It is interesting to note here that there is no steel tube approved for general use on aircraft in England with so low a carbon content. The nearest are T26 and D.T.D. 41. (See Chapter X.)

which when annealed or welded are reduced to

Tensile Strength . . .	>23 tons/sq. in.
Yield Point	17·8 tons/sq. in.



Welded Steel Tube Fuselage, Fokker C.V. Military Biplane

(courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

In long members it is only at the welded ends that the lower strength figures apply. At the mid-length of a strut, where the material is, of course, more highly stressed, the original normal strength may be taken.

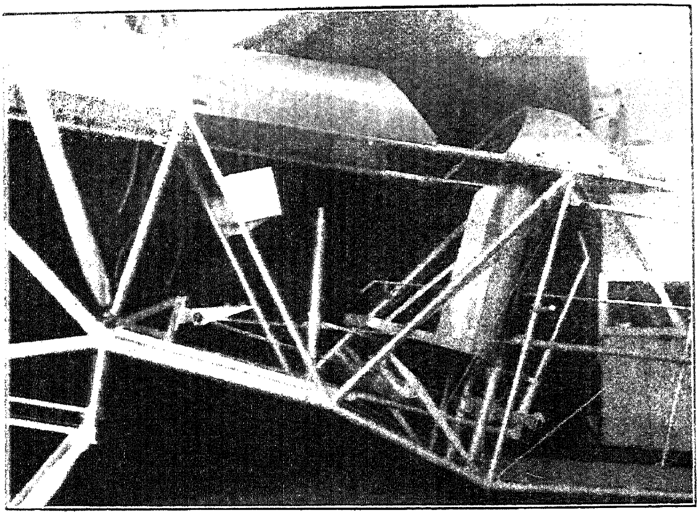


Fig. 229. Centre Portion of Fuselage, Fokker C.V.

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

For this reason such structures should have no welding on the struts except at their ends. Fokker uses friction clips for the attachment of equipment, etc.—a very sound practice. (See Figs. 228 and 229.)

It may be argued that a much lighter structure could be made of a steel with a higher tensile strength. The gain, consistent with durability, is thought by Fokker to be negligible, particularly as most of the struts are subject to column loading, in which case the modulus of elasticity is the main criterion of strength, a quantity which varies little whatever the grade of steel. Further advantages are that in some such mishap as a bad landing, the material is only bent locally and can be easily replaced. Again, when subject to alternating loads and vibration, this class of steel shows itself to be less subject to fatigue.

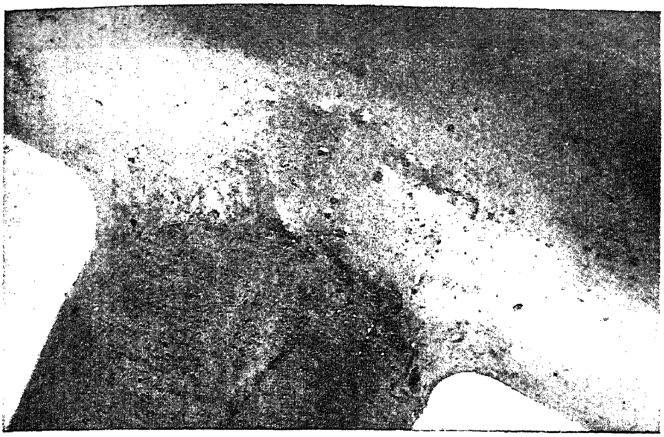


FIG. 230. BAD JOINT: TOO MUCH ACETYLENE USED

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

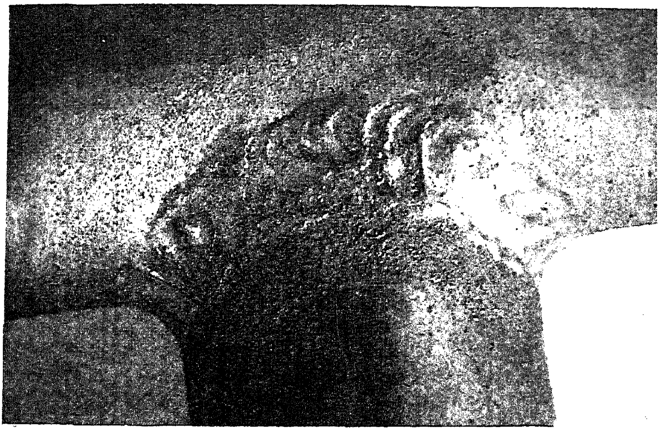


FIG. 231. BAD JOINT: METAL IS UNSUITABLE, CONTAINING TOO HIGH A PERCENTAGE OF CARBON

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

The strength of the welding is the strength of the fuselage as a whole. And herein lies the source of all the prejudice against the welded fuselage. Some experience is certainly necessary to judge good welding from bad. Figs. 230 to 235, reproduced here by kind permission of the Fokker Company, will be helpful, and are worth considerable study. They say in this connection—

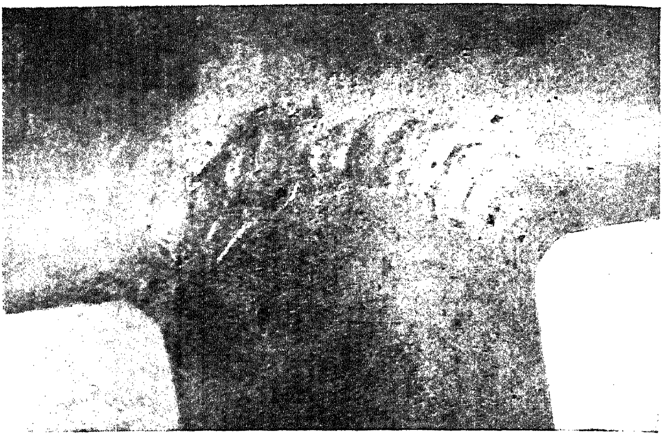


FIG. 232. BAD JOINT: TOO LITTLE WELDING WIRE USED AND WELDING DONE AT TOO LOW A TEMPERATURE

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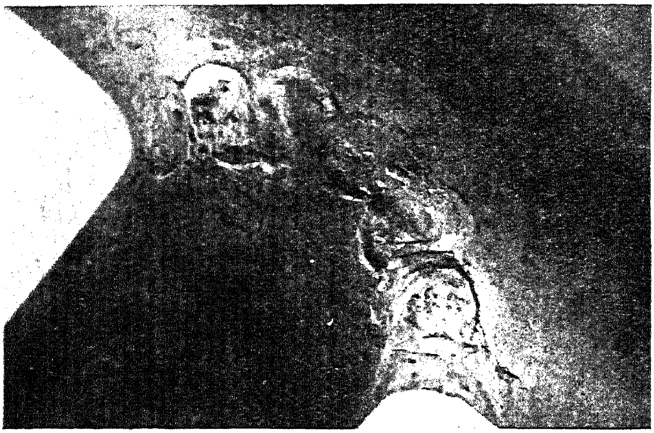

FIG. 233. BAD JOINT: TOO MUCH OXYGEN USED

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

"The rapidity with which a welder works is the best proof of his skill. Quick welding is good welding; slow welding is bad because it either results in the material being burnt or in irregularities. Practically speaking, too rapid welding never occurs as this is at once evidenced by the irregularities and uncovered spots.

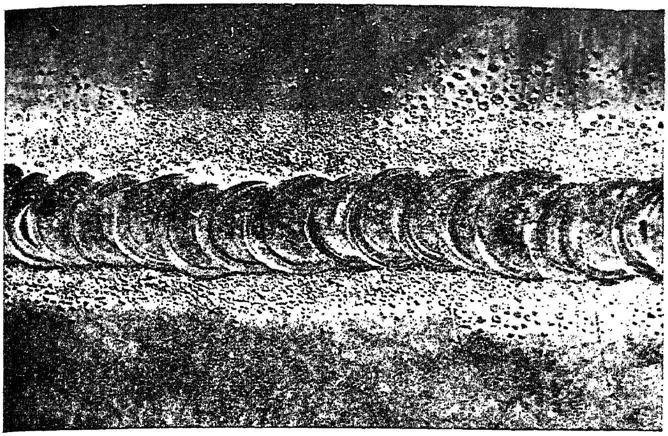

FIG. 234. SERVICEABLE JOINT

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

"One might say that good welding is not a primary essential, for the strength and reliability of the construction as such. This has been demonstrated, among other things, by the extensive tests made by the Dutch National Institute for Aeronautical Research at Amsterdam, with well and badly welded sections. The reliability of the entire structure is not dependent in the first place on the work of the welder, but chiefly on the work of the designer, who must know from experience

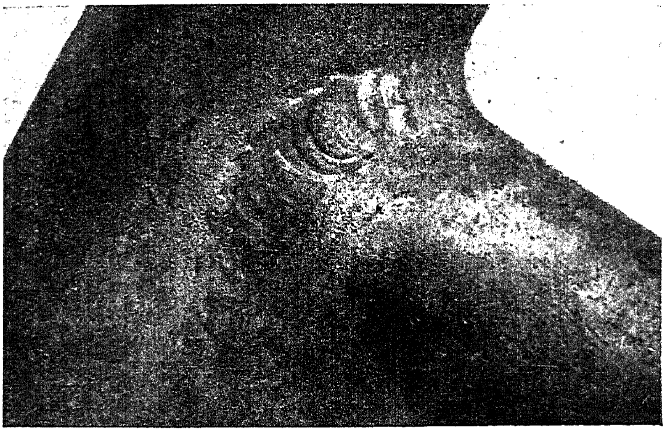

FIG. 235. SERVICEABLE JOINT

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

what can and what cannot be welded. He must construct logical joints and avoid abrupt transitions especially as regards the thickness of the tubes to be welded."

BRITISH AND AMERICAN WELDED FUSELAGES. Welded construction was taken up in this country many years after Fokker popularized it elsewhere. The principal reason for this tardiness was probably the use of the wrong materials in any experiments which were made. For there certainly were experiments and they appeared to show that welding was quite unreliable. and that the overheated steel cracked at the least provocation. The point which was not appreciated at the time was the necessity of using a low carbon steel which was malleable under all conditions. The tendency had been to use higher grade tubes, and the movement was in the direction of yet higher tensile strengths and the consequent higher carbon content. Such tubes undoubtedly are quite unsuitable for welding. Hence there arose a very considerable prejudice against the method. Both the Air Ministry and the constructors were agreed on this point.

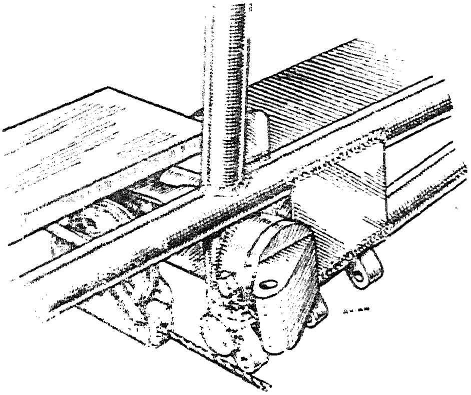

FIG. 236. AVRO "AVIAN" FUSELAGE JOINT
(*By courtesy of "Flight"*)

Fokker aircraft have, however. penetrated all the world's markets and shown a remarkable freedom from trouble. Their performance has proved the case, and welded fuselages have been produced by several of the principal British firms including A. V. Roe & Co., Ltd.; The De Havilland Aircraft Co., Ltd.; and the Fairey Aviation Co., Ltd.

The first of these—A. V. Roe & Co., Ltd.—built Fokker machines under licence and adopted Fokker methods for their own designs.

Fig. 236 illustrates the lower main plane spar and chassis strut attachments on the all-metal *Avian*. In this case it will be noticed that the big machined spar fitting is socketed into and bolted to the fuselage cross tube, but that the chassis fitting is completely welded in. The second and lower longeron tube added to carry this fitting and counteract the offset on the spar joint will also be noticed, together with the small bridge plate between the two longeron tubes. Similar methods have been used on later Avro machines, such as the *Cadet* and *Tutor*.

The De Havilland welded construction has been used successfully on a range of machines from the *Tiger Moth* to the larger *Puss Moth* and *Hawk Moth.* It is interesting in that it shows the introduction of additional safeguards.

Three joints from the *Puss Moth* are shown in Fig. 237. The engine

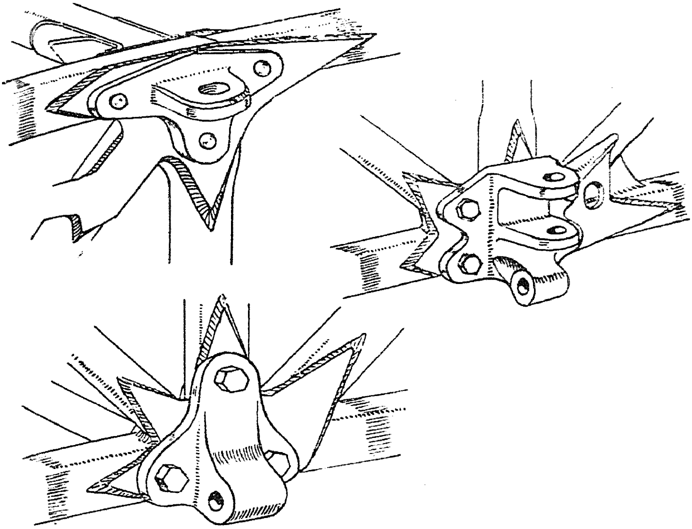

FIG. 237. DE HAVILLAND "PUSS MOTH" FUSELAGE JOINTS
(*By courtesy of "The Aeroplane"*)

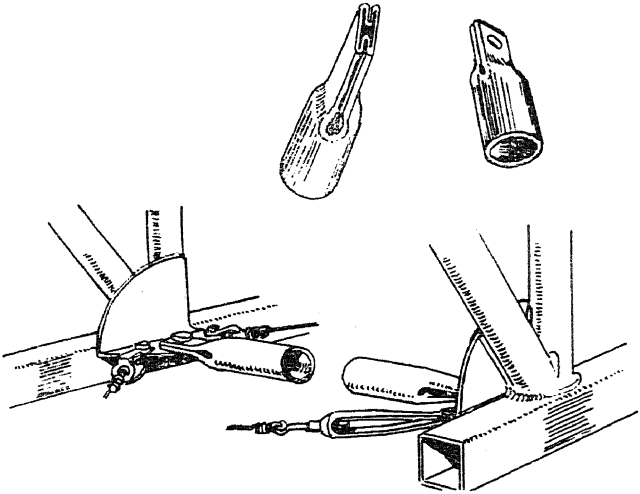

FIG. 238. DE HAVILLAND "HAWK MOTH" FUSELAGE JOINTS
(*By courtesy of "Flight" and "The Aeroplane"*)

bearers and cabin portion of this machine were made of square steel tubes and the rear end of round tubes. The joints illustrated all occur at attachment fittings of main plane spars or struts. These fittings were steel forgings bolted into position, not welded as in Fokker practice. The most striking feature of the design lay in the use of "shear plates" at all the joints. There was no welding in tension, and the addition of these plates ensured that the loads were all taken in shear on the welding, a type of stress which it is thought more capable of standing. No bracing wires were used in this fuselage, tubes acting as both struts and ties.

"Shear plates" were also used in the *Hawk Moth*, though in a slightly different way, as will be seen from Fig. 238. Here the cross bracing of the top and bottom panels was done with loose struts, bolted in, and wires, thus allowing the side panels to be made up as flat units, followed by a quick assembly into the complete structure. The ends used on the horizontal cross struts are extremely neat and simple, given the necessary tool.

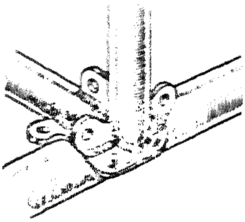

FIG. 239

(By courtesy of "Flight")

The Fairey method of construction makes use of welding, but with considerable restrictions, being confined to the cross panels of the rear end of the fuselage. The front and middle portions use machined joints.

In the rear portion the cross panels are made up as units with welded pressings as corner fittings. These pressings partly encircle the longeron tubes to which they are pinned or riveted. The longerons are thus not welded at all. (See Fig. 239.)

A more elaborate joint of similar design is shown in Fig. 240. This is on the lower longeron of the Fairey IIIF. The extension on the cross tube takes the rear catapult fixing. Except for the attachment to the longeron, the whole joint is made up with welding. The fitting provides a big bearing surface on the longeron and only the longitudinal components of the loads are taken in shear on the pins. The engine mounting is also made up with welding and a typical joint from the Fairey *Fox* is illustrated on p. 304.

Welding has been used very extensively in the United States for fuselage construction, a typical example of which was the Curtiss Robin (Fig. 24[illegible]). The heavily-loaded joints in the cabin and engine bearers had gussets welded in. In the rear portion of the fuselage, however, the connections were made merely by direct butt welding. This machine was a semi-cantilever high-wing monoplane, and the fittings for the wing roots and lift struts were welded in permanently. Unlike the Fokker construction, the fuselage was rigidly braced with tubes and there were no wires. The material was chrome-molybdenum steel.

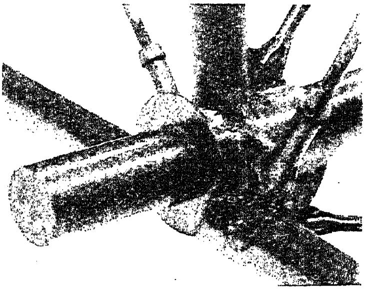

FIG. 240

(*By courtesy of the Fairey Aviation Co. Ltd.*)

THE MATERIALS OF BRITISH WELDED CONSTRUCTION. Experiments carried out on chrome-molybdenum steel for welding have not proved encouraging, in spite of the popularity of this material in the United States. It has shown a tendency to harden up and crack on cooling.

The tubes used principally in this country have been to D.T.D. Specification 41, and B.S. Specifications T35 and T45. They are all straightforward steels with a higher carbon content than the Fokker tube. D.T.D. 41 has a carbon content of 0·18 per cent and is rather cheaper and weaker than T35 and T45, which contain 0·3 carbon. These two are actually the same material, T45 being in the form of round tubes over ½ in. diameter, and T35 being round tubes below that size and such special sections as square, streamline and oval tubes.

The plate used for wiring lugs, corner piece pressings, etc., is usually to B.S. Specification S3, none of the higher grade steels being at all suitable for welding. For machined fittings B.S. Specification S21 is usual, although S1 may be welded if the fitting is small and can afterwards be normalized.

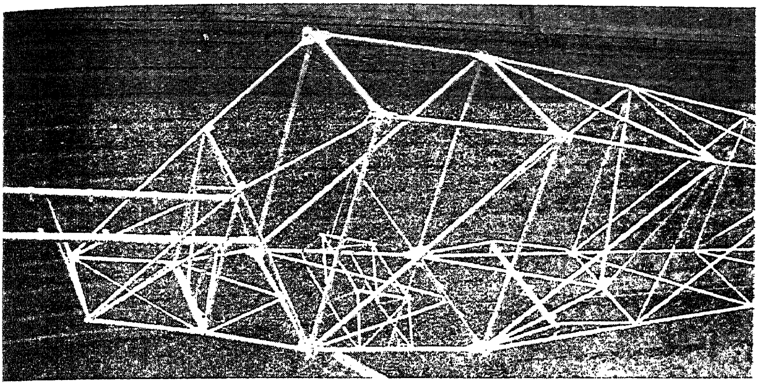

FIG. 241. CURTISS "ROBIN"—FUSELAGE STRUCTURE

(By courtesy of the Curtiss Aeroplane & Motor Co., Inc.)

Further particulars of these materials, their constituents, properties and strengths are found in the tables in Chapter X.

AIR MINISTRY REGULATIONS ON WELDING. The use of welding is still restricted for both civil and military aircraft, the regulations being given in A.P. 970 and A.P. 1208. In these it will be seen that a second path for the load must always be provided where a welded member occurs. The efficiency of the joints is similarly the subject of pessimistic assumptions.

The use of dissolved acetylene is encouraged by the placing of stringent tests on gas generated from carbide in the aircraft factory.

Specimens of each welder's work must be examined and tested periodically under the supervision of the A.I.D.

In stressing a welded fuselage, the Air Ministry requires that it shall be regarded as pin jointed. This appears to be an unfair assumption, but the justification for it lies in the lower stress which is developed at the welded joints. In some cases a factor of fixity may be allowed if a strong argument can be made in its favour.

Electric arc welding is prohibited unless special permission has been obtained. Electric spot welding is, however, coming to be recognized. The process is described on p. 374.

WELDING JIGS AND PRACTICAL CONSIDERATIONS. Some mention has already been made of the jigs used by Fokker in the building of fuselage structures. It is extremely difficult to lay down rules for jig design. It has been said that the whole art lies in one's ability to profit by one's own mistakes. The simplest jig is undoubtedly the best, and its very simplicity hides the extent of its designer's experience.

The use of a jig to hold the work during tack-welding is quite essential. The usual materials are heavy structural steel members firmly bolted together, or iron castings. The expense of the latter is justified by big production, but the former is quite cheap and suitable for experimental work and small batches.

The jig must have considerable rigidity to hold the tubes correctly against movement. But expansion and contraction in heating and cooling must not be restricted in any way. A jig for constructing the side panel of a fuselage may hold the vertical struts in slides or notches so that they may expand easily. The longerons may then rest between these strut ends and some solid backing member with an expansion tolerance of 0·05 to 0·10 in., according to the size of the work. No bulky clamps or supports should be allowed near a welded joint where the mass of metal would too quickly conduct the heat away. A common fault is to make the removal of the finished part a lengthy process by the use of too many screwed-up clamps and supports.

The progression of welding to give the least distortion is rather a matter of trial with each particular job. A sound rule is that one end of a tube should never be welded until the other is quite cold. This applies particularly to redundant structures, and to ignore it is to cause contraction cracks at both ends. This suggests that the correct progression is to start at one end of one longeron and work along its length before going to the other.

When the whole fuselage with both sides, top and bottom is being finally welded into one piece, two welders may work together if they take opposite ends of the same tube, provided that there is no restriction on contraction. The position is much more complicated when we pass to an engine mounting. Only experience of the particular design can give the best results.

Rotating jigs are frequently used and much reduce the manual labour of the welder.

Cracked joints, which may appear after some service, may often be traced back not to faulty welding or material, but to an incorrect progression which has resulted in high initial stresses being set up.

Similar causes, operating in different ways, are at the bottom of most cases of cracking. As has been stated in Chapter II, a change of volume takes place when steel freezes. The metal contracts and must be allowed to do so. If it is restricted, the work will be faulty. The restriction may result from the contraction of other joints in the fuselage, from the rigidity of the jig, or from purely local causes. Thus in butt welding two plates together, the work should begin in the middle, not at the edge, to allow of a more even dissipation of heat.

Where the plates tend to pull apart on cooling, a compensating compression applied either by actual loading or by heating of the surrounding material may prevent cracking.

Designers are frequently tempted to call for welding on both sides of such joints as tees. This is not good practice. The contraction on cooling of the first side welded sets up internal stress which may relieve itself in the form of a crack when the opposite is subsequently heated up. It must be remembered that when hot, no steel is as strong as when cold.

It was noted in Chapter II that the longer steel is retained at a higher temperature, the coarser will be its granular structure. Welding must therefore be done quickly, and the temperature not raised higher than is necessary. Furthermore, the torch flame must always be kept neutral. If a large granular structure forms up and oxygen from the flame be allowed to penetrate it, an intergranular film of oxide will occur. The steel is then in the burnt condition and cracks are inevitable.

A further cause of cracking may be the state of internal stress due to cold work on the parts before welding. This stress should be relieved by normalizing wherever possible. When the cold work has been very local, however, it may be sufficient to pass the flame quickly over the part before welding. This pre-heating should not be more than sufficient to raise the temperature to a barely visible red heat.

It is not sufficient to blame the material when trouble occurs. These precautions are necessary and, in justice to any steel, should be observed. An investigation from first principles will show most of the trouble to be due to inexperience or thoughtlessness on the part of either the designer or the welder.[1]

CORROSION PROTECTION OF A WELDED FUSELAGE. No type of construction is easier to protect from rusting and corrosion than a welded structure. Once the fuselage has been welded up so that all the tubes are hermetically sealed, their interiors need no further thought. The design should allow for this and should be watched at all points so that there can be no ingress whatsoever. The exterior of the tubes and joints should then be wire-brushed to remove scale and given a coat of any good rust-resisting paint, which may need renewing periodically at points of wear.

2. Tubular Fuselages with Mechanical Joints. British designers were slow in taking up the welded fuselage. But they had been exercising their ingenuity in other ways. Apart from the monocoque and metal skin structures already dealt with, they have evolved a variety of methods of using tubes with mechanical joints. By a "mechanical joint" is meant one made up with bolts, pins or rivets, as opposed to the welded joint, which is permanent and cannot be taken apart. The joint pieces may be either plate pressings, socket fittings machined from solid, or stampings machined to finish.

Many arguments have been put forward in favour of the mechanical joint, and undoubtedly there is much to be said for it in its simpler forms. A much greater range of materials is available—stainless and high tensile steels, duralumin, etc. In some cases there may be an advantage in using tubes of a larger diameter and thinner gauge than would weld satisfactorily. But this must be viewed in conjunction with the stability of the tube wall against service and handling loads, and the additional weight of end fittings.

The labour available and the quantity of production may be the

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[1] See *Aircraft Engineering*, Jan., 1934, "Shop Practice in Welding," by W. Gibson. Readers are also referred to the following American sources: (1) N.A.C.A. Report No. 348 "Strength of Welded Joints in Tubular Members for Aircraft." (2) "Airplane Welding," by J. B. Johnson (The Goodheart-Willcox Co., Chicago). (3) "The Cause and Prevention of Heat Cracks in Aircraft Welding," H. S. George, read before Fifth National Meeting of the A.S.M.E. Aeronautics Division, Baltimore, 12th-14th May, 1931.

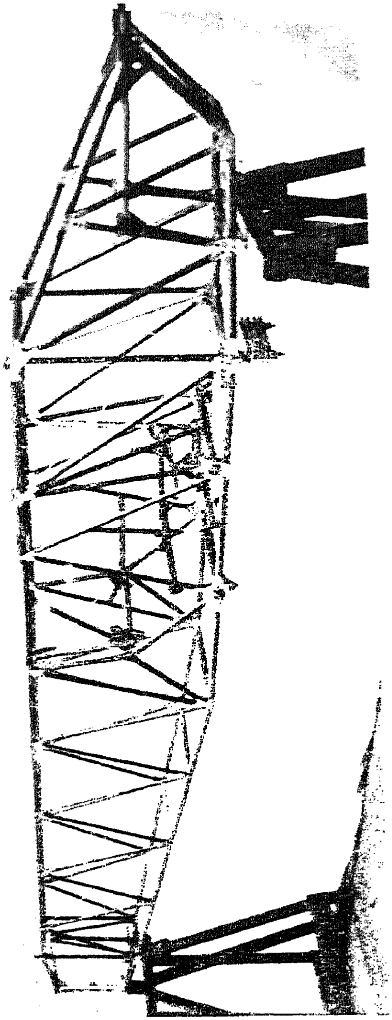


FIG. 242. HAWKER FUSELAGE CONSTRUCTION

deciding influence. When the quantity is large and allows the use of plate pressings and parts machined in a capstan lathe, which can be assembled by unskilled labour, then a very cheap yet sound job may be made. This is the justification for the Hawker construction. (See Fig. 242.)

The side panels are built as warren girders with flitch plate joints. Either square or round tubes may be used. The squaring of the ends of a round tube is the work of a few moments in a suitable roll. It is claimed that a range of six different flitch plates are sufficient for all requirements in any machine up to "day bomber" size. Similarly only four sizes of wiring lugs are needed for all horizontal and bulkhead panels, which are wire braced. The cupped bolt is a straightforward capstan job. The tubular rivets may be to T50 or any lower grade of steel, the spinning over being an easy operation.

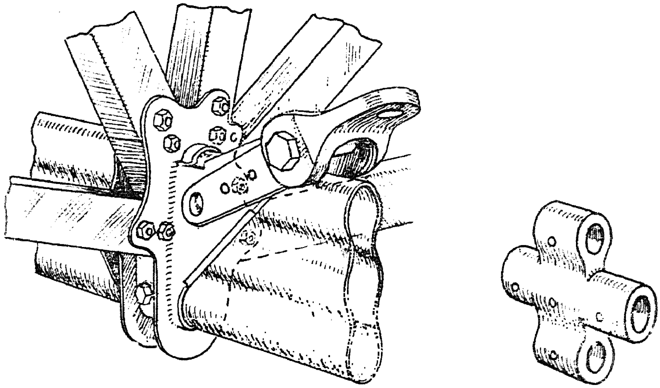


FIG. 243. GLOSTER FUSELAGE JOINT

(*By courtesy of "Flight"*)

The assembly jigs are particularly simple. In case of an emergency, expansion of production could be as fast as the supply of materials allowed, and if one specification were not available, several others could be used instead. Most of the work can be done by semi-skilled labour, and it is more suitable, so the manufacturers claim, than any other system to be handed out to sub-contractors.

Very similar methods of fuselage construction have also been developed in this country by the Westland and Blackburn firms.

A joint from a Gloster fighter is illustrated in Fig. 234.

The corrugated section is the fuselage cross member opposite to the front spar of the lower main plane, and is a type already discussed in Chapter III. It will be noticed that the point is one of great concentration of loads, which reach it from both engine and tail, the weight of the aircraft and the lift of the main planes, combined with a component of the undercarriage load. In spite of this, the design has been completed with commendable simplicity. There are apparently no offsets, and the loads, split into the two side plates, balance out directly. The only expensive part is the aluminium alloy plug, which is inserted into the spar tube, the cost lying in making it a good fit. The cheapness of the solid drawn spar tube, however, allows of small extra expenses of this kind.

A very forceful attack on the weight problem led Boulton & Paul construction into new paths. The first great difference is in the tube used. Owing to the allowance which must always be made for eccentricity in solid drawn tube, they have introduced a new type of "locked joint" tube which is produced from strip on a draw bench (see Fig. 244). This tube can be produced in a wide range of sizes and shapes in both steel or duralumin. In the example shown the tube is of high-tensile steel of a larger diameter in relation to its thickness than would be possible if solid drawn. The beading at the joint shifts the neutral axis of the tube slightly off centre towards itself, but since the tube is of uniform wall thickness and the joint is along a straight line, the neutral axis remains straight. Any eccentricity of loading due to the fact that the load is applied along the central axis of the tube, whereas the neutral axis is slightly displaced, is calculable and is claimed by the manufacturers to be very small compared to the effective curvature of the neutral axis of normal solid drawn tubes. When the tubes are subject to side load, the bead is placed on the compression side, where it acts as a local stiffener.

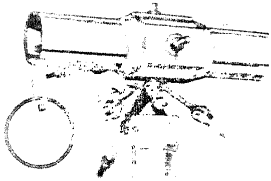


FIG. 244

(By courtesy of "The Aeroplane")

In the Boulton Paul Mail Plane, the methods shown in Fig. 244 were modified to make greater use of pressings instead of machined fittings, at least in the rear end of the fuselage. This is illustrated in Fig. 245.

The longerons were made of high-tensile steel closed joint tubes of the type described above. The vertical and horizontal struts were of round duralumin tube, but, at the joints, the tube ends were squared off. An L-shaped plate with two corrugations passed round the longerons to both vertical and horizontal struts. Angle and channel pieces were used on the inner side of the longerons. The fastenings were made with T-shaped shear bushes which were held in place by threaded spokes. These bushes, together with the doubling plates on the tube ends, ensured that the bearing area was adequate.

One of the lower wing root joints is also shown in Fig. 245. It will be seen that the lift wires were carried over on to the fuselage side, where they were taken on to a wiring lug bent under the upper hinge fitting. In the front portion of the fuselage, where the loads were much heavier, certain of the struts were of steel tube and machined fork end sockets with bolted connections were used in making up the joints. These sockets were attached to the tubes with the shear bushes previously described.

Foreign Examples of Tubular Fuselages with Mechanical Joints. Caproni. Somewhat similar in type to a number of earlier British fuselages with mechanical joints is that of the Italian trimotor monoplane, the *Caproni* 101. This is shown in skeleton in Fig. 246, the wing construction of which has already been described on page 151.

The principle underlying the structure is that welding shall be used for making the joints, yet high-tensile nickel steel tubing, which is, of course, not weldable, forms the material of the longerons and struts.

The rear part of the fuselage consists of rectangular bulkhead panels with the longerons passing through the joint sleeve at each corner. These panels are all cross braced with high-tensile steel wires, having

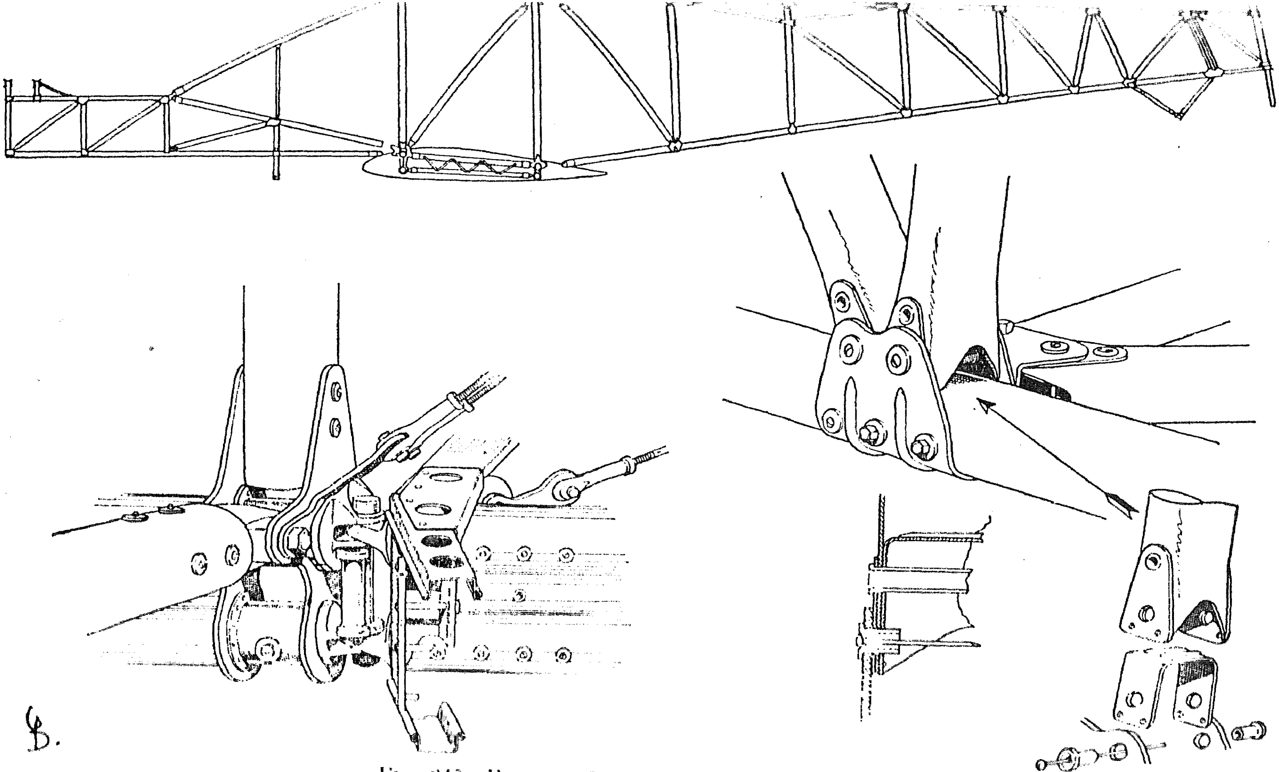


FIG. 245. BOULTON PAUL "MAIL PLANE" [illegible]

ends. A typical joint in the forward part of the fuselage where the diagram is more complicated, has already been shown in Fig. 174.

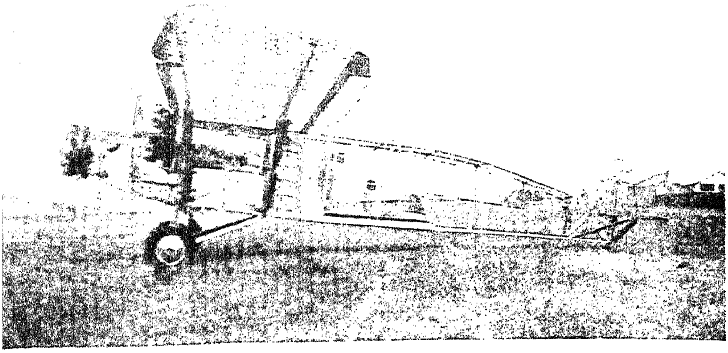


Fig. 246. Caproni 101—Skeleton Structure

(By courtesy of Aeroplani Caproni Società Anonima)

The joint pieces are made from low-carbon steel, either tube or plate. It is welded up in the form of a branch piece (see Fig. 247), each tubular member coming into the joint being provided with a socket.

Bracing wires are taken on lugs which are fitted into slots in the appropriate sockets and welded. Each socket end is machined off to a slight taper so that there shall be no sudden change of section. After welding, the joint piece is heat treated at normalizing temperature to remove internal stress. It is then sandblasted and tinned. The connection of the tubular members into their sockets is made with sweating and further secured with bolts.

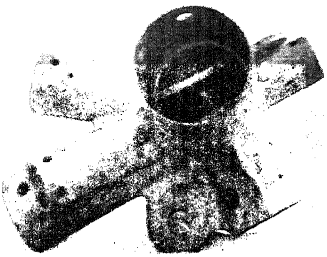


Fig. 247. Caproni 101—Fuselage, Joint Piece

(By courtesy of Aeroplani Caproni Società Anonima)

To protect the structure against corrosion, the main tubes are oiled internally and tinned externally. All the tube ends are sealed so that there shall be no possible ingress of moisture.

Letov and Avia. Whilst the front and rear ends of the Letov 231 were of welded chrome molybdenum tubing, the centre portion was built up of round tubes, squared at their ends and jointed with cover plates and tubular rivets after the manner of the Hawker structures. (See Fig. 242.)

In the Avia 534 single seat fighter, the fuselage was built of high-tensile steel tubing, cross braced with wires and covered with fabric. A typical fuselage joint is shown in Fig. 248.

3. Strip Construction. The same considerations which led Boulton & Paul to introduce their "locked joint" tube were a deciding influence in an earlier Bristol fuselage design. The result was rather different. High-tensile steel strip, to some such specification as S.88, was drawn in semi-circular sections with interlocking lips at their edges which were pulled together to form tubes. This made possible an entirely different kind of joint (see Fig. 249). Wire bracing was dispensed with in the side and horizontal panels, and gusset plates were riveted into the tube ends.

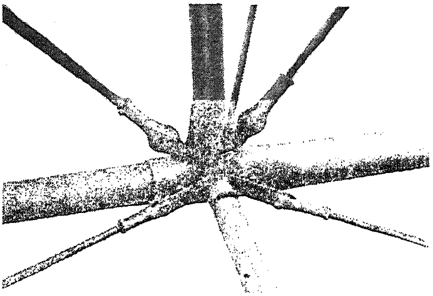


Fig. 248

Avia Fighter, Typical Fuselage Joint

(By courtesy of Avia)

Where a very big load was to be carried, the tube was corrugated in order to develop a higher stress.

The details of the Bristol *Bulldog* (Fig. 250) illustrate how the fairing structure was added to the main fuselage structure.

It was claimed for the "Bristol" strip fuselage that a very considerable weight reduction was achieved, not only by the use of high-tensile steel in large concentric tubes, but that the method of making the joints resulted in a fixing of the strut ends which reduced the stress in the members.

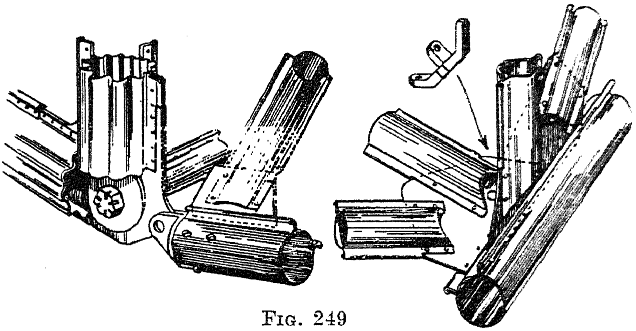


Fig. 249

(By courtesy of "Flight")

Steel strip construction of a different type was used in the Armstrong-Whitworth *Atalanta* (Fig. 251). A number of standard sections were devised which were riveted together in different arrangement to form channel girders. The fuselage had four longerons throughout, but the side panels of the centre portion were warren braced, whereas in the rear there were vertical struts, and wire cross bracing was used.

Where the struts were heavily loaded the sections were braced with small flanged strips at intervals. The riveting, throughout the machine, was all very accessible, and the joints, which were made with gusset plates on each side of the members, were simple. In the rear end, the gusset plates were extended to form double wiring lugs. Doubling pieces were riveted on to increase the bearing area where the shackle bolt passed through. The front spar attachment joint, *A*, was made up with a robust drop forging bolted through. The centre portion of the fuselage

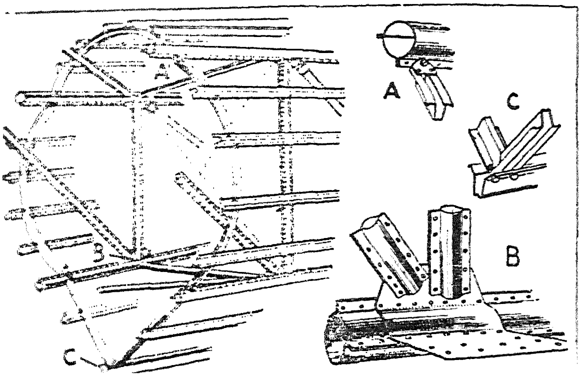


FIG. 250. BRISTOL "BULLDOG" FUSELAGE
(*By courtesy of "Flight"*)

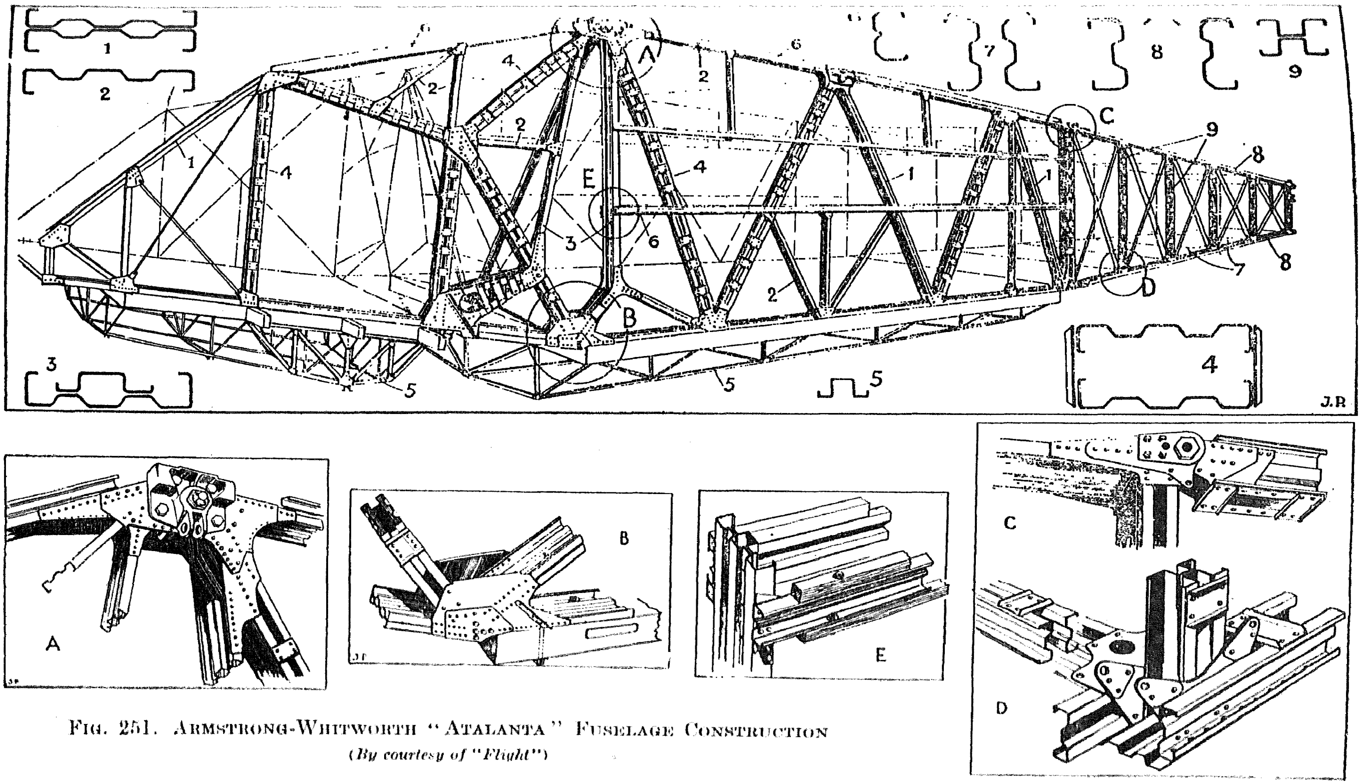
was covered with three-ply, which was screwed to light wooden stringers. These, in turn, were bolted to light channels riveted to the main members (see *E*). The rear end was fabric covered.

Another example of strip construction in a fabric covered fuselage comes from Russia in the Stal II, designed by Poutiloff. Stainless steel is used throughout and the members are corrugated somewhat in the manner of the Bristol fuselage shown in Fig. 249. Electric spot welding (see page 371) is used for building up the members instead of the usual riveting or the tight beaded joint of Bristol. The fuselage sides form Warren girders. The longerons are not continuous and there is a bolted spool at each joint. Straight members run across from side to side at each joint and the panels are cross braced with wires. The details of this structure including the method of carrying the floor are shown in Fig. 252.

Vickers Geodetic Construction. The principles of geodetic construction were described on page 96. The *Wellington* bomber fuselage has a number of main transverse frames, as will be seen in Fig. 253. The geodetic bracing structure is built up on the longerons in long panels and assembled on the transverse frames.

The basic structure is thus complete and may be taken off the assembly jig for the installation of the equipment and the addition of the fabric covering.

The details of this structure are very unusual and of great interest. For example, the longerons are not attached directly to the frames (see Fig. 254).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J.R

FIG. 251. ARMSTRONG-WHITWORTH "ATALANTA" FUSELAGE CONSTRUCTION

(*By courtesy of "Flight"*)

Where the [illegible] members cross the face of the frame they are fastened to it by means of flat plates bolted to the frame. The longeron itself merely passes by.

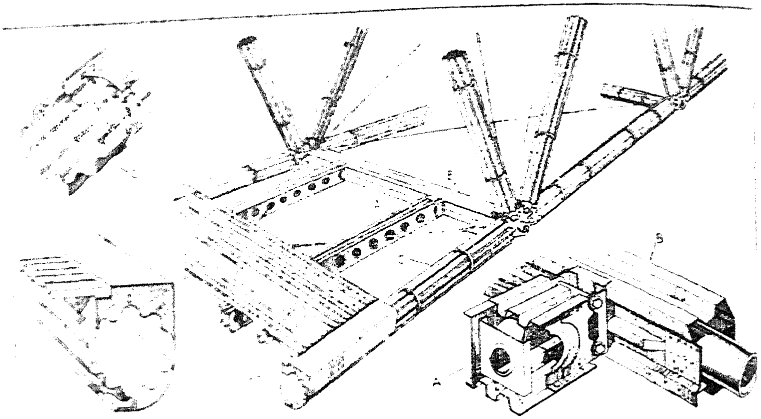

Fig. 252. The Fuselage Construction of the Russian "Stal II"
The whole machine is built up of [illegible] sections of very thin gauge stainless steel, shot-welded [illegible] system
(*By courtesy of "Flight"*)

Details of the geodetic panels are given in Fig. 255. From this it will be seen that the attachment points of the top and side bracings are staggered. This, of course, introduces offsets in the loading of the longeron but the actual stresses are probably quite small.

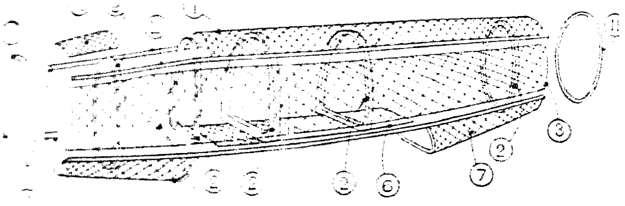

Fig. 253. Vickers "Wellington" Geodetic Fuselage
(*By courtesy of "The Aeroplane"*)

Where two bracing members cross, they are "halved" into each other. The flange of each, which is cut away, is made good by a riveted fish plate, and the two bracings are connected together by two "butterflies," riveted each to their respective member and having a bolt passing right through. The butterflies are pressed from a standard extruded section. The method of rolling the bracing members from flat duralumin

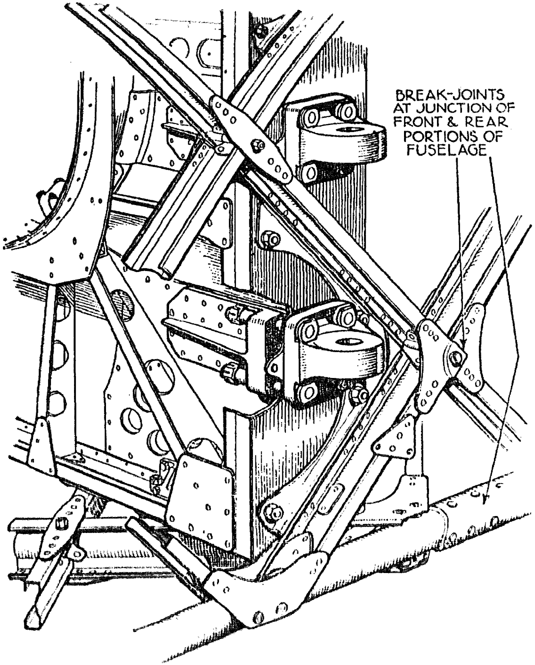
BREAK-JOINTS AT JUNCTION OF FRONT & REAR PORTIONS OF FUSELAGE

FIG. 254

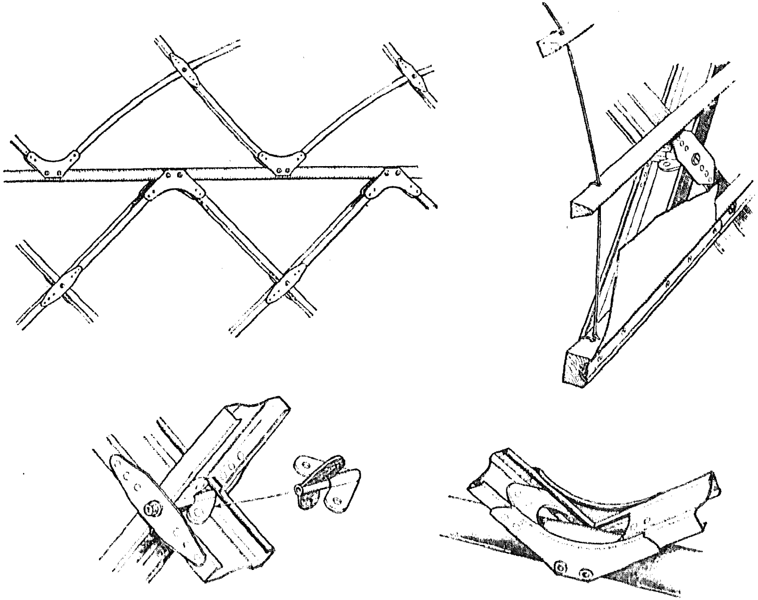

FIG. 255

FIGS. 254–5. VICKERS "WELLINGTON" FUSELAGE JOINTS

(*By courtesy of "Flight"*)

strip so that they take on their correct cross-section and curvature is described on page 345.

The fabric covering passes over the top of light stringers, the intermediate ones being merely located by cords. Only the main fabric stringers are fastened to the structure. Once the fabric has been tautened by dope there is little tendency for it to pull away. To end the fabric on the main stringers, a groove is cut in them and the fabric, trapped under a strip, screwed in.

CHAPTER V

FLYING BOAT HULLS AND SEAPLANE FLOATS

FLYING BOAT HULLS

THE basic idea of the flying boat hull is in part the same as that of the fuselage, as described at the beginning of the last chapter. It must perform all the functions and possess all the qualities demanded of the fuselage, and to these must be added many others to suit it for its marine requirements. Not only must the hull be clean in the air, but clean when running on the water—two qualities which are rarely in accord with one another. The step and chine so necessary below could well be dispensed with above. As a floating body, the hull must be stable both laterally and longitudinally when at rest, in waves, and when running on the surface. And it must be strong enough to withstand all the air loads which are imposed on it as part of a flying machine, together with the water loads which result from its being a boat.

The hydrodynamical design, like the aerodynamical design, is too big a subject to be included in the present book, and will only be dealt with in its influence on the structural design.[1]

The Terminology of Flying Boat Hulls. The naval architects who have come into aeronautical work to perfect the flying boat hull have brought with them all the terminology of ships. Those readers who are unfamiliar with it may find Figs. 256 and 257 of help in understanding this chapter.

Referring to Fig. 256, the overall dimensions—*length*, *breadth* (or *beam*) and *depth*—are spoken of as *moulded* when they are taken inside the plating or skin—i.e. to the dimensions of the *moulds* or templates from which these sizes are laid out.

The *draft* is the dimension vertically downwards from the *load water line* to the lowest point of the hull, whilst the *freeboard* is the dimension vertically upwards from this line either to the deck edge (*gunwale*) or to the lowest opening through which water could enter the hull, whichever of these is less.

The *dorsal* is the centre line of the deck along the top of the hull. *Gunwale*, *chine* and *keel* require no more explanation than is given in the illustration.

Tumblehome is an inward slope of the side from chine to gunwale, and *flare* an outward slope, usually associated with a steep curve towards the gunwale. These two may occur on the same hull, *flare* at the stem and *tumblehome* along the rest of the length.

The meanings of the main structural terms will be evident from the three sections. A *strake* is a longitudinal line of shell plating. Certain strakes have special designations of their own. That next to the keel is known as the *garboard* strake, and the one immediately below the gunwale as the *shear* or *topside* strake.

The Strength and Structural Design of the Hull. Unless many assumptions are made the problem of determining the stresses in a hull structure is extremely complex, and designers have worked more by eye and experience than by figures.

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[1] See *Seaplane Float and Hull Design* by the author (Pitman) for the hydrodynamical design. Also *Marine Aircraft Design*, Munro (Pitman).

Owing to the instability of thin materials in compression, it is difficult to estimate the contribution of the shell to the strength of the boat. Papers before the Institution of Naval Architects, by Professor Abel[1] and Professor Inglis[2] have discussed the behaviour of stiffened thin plating under water pressure. An investigation on these lines, combined with destruction tests on full scale panels, may be used in deciding the thickness of skin required on the more heavily stressed portions of the planing bottom near the front and rear steps. But the quantitative value of the load which must be catered for is still in doubt and may vary with the angle of the V bottom. Tests which have been carried out in this country[3] and in America[4] appear to show that the worst

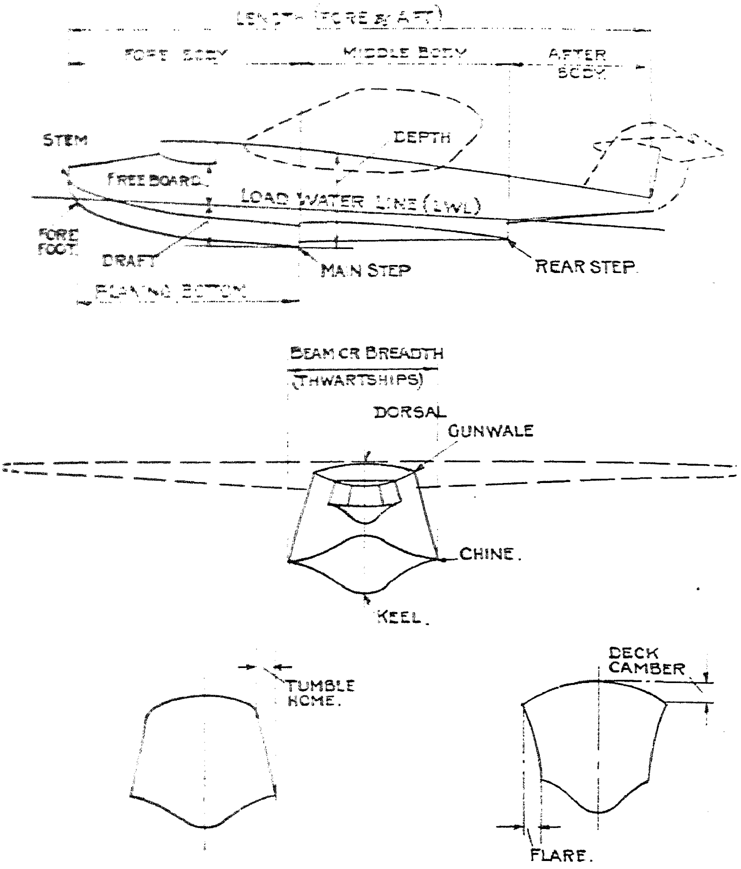
LENGTH (FORE & AFT)
FORE BODY
MIDDLE BODY
AFTER BODY
STEM
DEPTH
FREEBOARD
LOAD WATER LINE (LWL)
FORE FOOT
DRAFT
MAIN STEP
REAR STEP
PLANING BOTTOM
BEAM OR BREADTH
(THWARTSHIPS)
DORSAL
GUNWALE
CHINE.
KEEL.
TUMBLE HOME.
DECK CAMBER
FLARE.

FIG. 256

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[1] *Trans. I.N.A.*, 1923, Vol. LXV, p. 161.
[2] *Trans. I.N.A.*, 1925, Vol. LXVII, p. 145.
[3] R. & M. 683, R. & M. 926, *Aircraft Engineering*, August, 1930.
[4] N.A.C.A. Report No. 290.

loading on a V-bottom hull will be of the order of 6–8 lb. per square inch. A later American report[1] put it as high as 15 lb. per square inch.

The Air Ministry requirements for hull strength are stated in the R.A.F. *Design Requirements*, A.P.970, and the *Airworthiness Handbook for Civil Aircraft*, A.P. 1208. These consider the strength of the attachments of super-structure to the hull and the strength of the hull itself as a beam. They also give a pressure distribution diagram to be used in stressing the planing bottom when the angle of V is between 150° and 140°. This assumes a maximum loading of the order of 8 lb. per square inch.

Mr. A. Gouge, B.Sc., F.R.Ae.S., has given[2] a method of stressing any hull up to an "all-up weight" of 70,000 lb. The keel, frames and stiffeners are treated as beams carrying the load, which is transmitted to them by the skin. The after body takes only air load from the tail and is investigated for terminal nose dive. There are also bending and torsion, due to fin and rudder loads. But without full scale tests the strength is as indeterminate as a monocoque fuselage. For the light top deck he suggests taking a loading of 250 lb. per square foot as a basis for the estimation of stringer and deck beam strength.

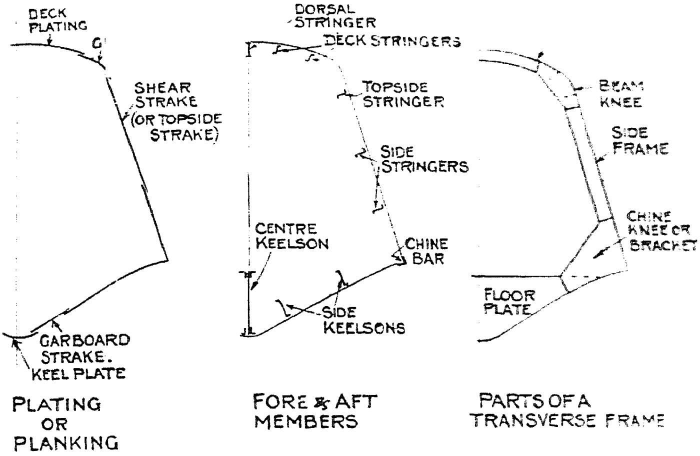
DECK PLATING
C
SHEAR STRAKE (OR TOPSIDE STRAKE)
GARBOARD STRAKE.
KEEL PLATE
PLATING OR PLANKING
DORSAL STRINGER
DECK STRINGERS
TOPSIDE STRINGER
SIDE STRINGERS
CENTRE KEELSON
CHINE BAR
SIDE KEELSONS
FORE & AFT MEMBERS
BEAM KNEE
SIDE FRAME
CHINE KNEE OR BRACKET
FLOOR PLATE
PARTS OF A TRANSVERSE FRAME

FIG. 257

Experience has shown that average scantlings for a typical 45-ft. hull built in duralumin or "Alclad" alloy and of the form and construction shown in Fig. 257 would be as follows—

Shell plating . .	Bottom 14 s.w.g. at front step to 16 s.w.g. forward and 18 s.w.g. aft. Sides 16 s.w.g. amidships to 18 s.w.g. forward and 20 s.w.g. aft. Deck 18 s.w.g. amidships to 20 s.w.g. at ends.

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[1] N.A.C.A. Report No. 346.

[2] "The Design of Seaplanes," *Aircraft Engineering*, August, 1930. "Design and Construction of Flying Boats," Inst. Eng. and Shipbuilders in Scotland, 24th March, 1931.

Keel plate . .	14 s.w.g. at front step to 16 s.w.g. at ends.
Centre keelson .	18 in. deep × 16 s.w.g. amidships, tapering in depth to 6 in. and in thickness to 18 s.w.g. forward and 20 s.w.g. aft. Top and bottom angles, $\frac{3}{4}$ in. × $\frac{3}{4}$ in. × 16 s.w.g., tapering in thickness as for the keelson. The vertical keelson plate may be lightened with flanged holes and stiffened by corrugations or channels riveted on.
Dorsal . . .	Two channels $2\frac{1}{2}$ in. × $\frac{5}{8}$ in. × 18 s.w.g. back to back, riveted together, with $1\frac{1}{2}$ in. diameter lightening holes in the webs.
Side keelsons . .	Z-sections 4 in. × $\frac{3}{4}$ in. × 18 s.w.g. (with lightening holes) over the fore body, tapering out towards the step and stern. Cut at each frame and gusseted.
Chine angle . .	$1\frac{1}{2}$ in. × $1\frac{1}{2}$ in. × 16 s.w.g. amidships, tapering to ends.
Side stringers . .	Z-sections 3 in. × $\frac{5}{8}$ in. × 20 s.w.g., tapering out towards the ends. Cut at each frame, and gusseted.
Deck stringers .	Z-sections or angles 2 in. × $\frac{5}{8}$ in. × 20 s.w.g., tapering out towards the ends. Cut at each frame and gusseted.
Transverse frames .	Spaced 24 in. apart. Floor plate: 18 s.w.g. with $\frac{3}{4}$ in. flange at top. Shell angle $\frac{3}{4}$ in. × $\frac{3}{4}$ in. × 18 s.w.g. Chine knee: 18 s.w.g. Side frame: Z-section 3 in. × $\frac{5}{8}$ in. × 18 s.w.g. Beam knee: 18 s.w.g. Deck beam: Z-section or angle 2 in. × $\frac{5}{8}$ in. × 20 s.w.g.

Several of the frames, as dictated by the buoyancy calculations, are made as watertight bulkheads so that in the event of one compartment being flooded the others will keep the boat afloat. The change of trim, as determined in these calculations, will show whether it is necessary to carry each bulkhead right to the top of the boat.

Where, owing to limitations of plate sizes, it is necessary to make a break in the keelson girder it should be made good by butt straps. Such breaks should, of course, occur between frames. This will give an opportunity for making the changes in thickness towards the ends. It will hardly be necessary to make any special provision for a break in the bottom angles of the keelson, as the plating will transmit the load the break. Cuts in the top angles should be made good by a butt strap over the free open edge. Care should be taken when designing to see that such breaks occur at as widely varying places as possible. It would be a point of great weakness, for example, if a break in each of the four angles and also of the plate of a girder were allowed in the same frame space. Regarding the keelson as a continuous beam across the frames, it will be seen that there will be points of contraflexure with no bending moment at one-third to one-quarter of the frame spaces from the frames. These are therefore the most suitable positions for breaks in all such structural members as the keelson, even though made good with butt straps.

In order that the keel plate may be easier to replace after wear and damage by grounding, it is good practice to make it an "outside strake"—that is, to have its edges overlapping the garboard strake, as seen from the outside. The other strakes should be overlapped at their lower edges, and therefore underlapped at their top, or "clinker built." All laps and edges should be double chain riveted.[1] Since the strakes cannot be run unbroken from end to end of the boat on account of the limitations of plate sizes, vertical laps must be arranged. They should be spread apart from each other as far as possible, and there must always be a complete frame space between the vertical laps of adjacent strakes. Nor should a lap come in the centre of a frame space, but be placed as near as possible to a frame. The stiffening effect of the angle will then to some extent prevent the stretching of the plate edge under the action of the riveting hammer and stop the destructive drumming that would occur.

To preserve watertightness the rivet spacing should not be greater than four times the diameter of the rivets. The joints may be made up with marine glue, and a thread of caulking cotton inserted between the lines of rivets. Caulking is, of course, impracticable with such thin plating as is used on flying boat hulls. A point of leakage may occur where a vertical lap meets a longitudinal plate edge (see Fig. 258).

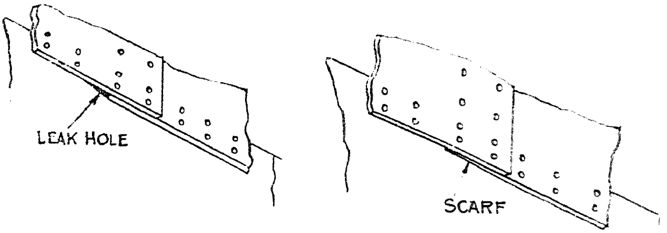

FIG. 258

The inner edge of the sandwiched plate should be rubbed off or "scarfed" with a file at that point so that the outer plate will bed down continuously.

It is in the plating, perhaps, more than in any other part of the hull structure that the advantages of straight line construction show themselves. Panel beating is eliminated and with it the process of annealing the shell plates. They may be used in the hard condition as supplied since the only work done on them is cutting to shape and drilling for rivets.

Frames and stringers, etc., are now usually extruded sections but they may be produced on the drawbench, by rolling, or by folding. Here again it is an advantage to cut out annealing. If the cross-section of the member is simple, it may be attained whilst the material is in the soft phase following heat treatment and before age-hardening sets in. The reduction in cost will be very considerable.

Contour members such as the keelson, and the dorsal at its ends, cannot be drawn or rolled. They are, therefore, designed as flat plates, cut to contour with bent boundary angles riveted on. The slightly curved contours of stringers may be achieved by rolling them to template immediately they come off the draw bench or folder. Although the process of building is described later, these points are mentioned here on account of their influence on design.

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[1] See Chapter IX for appropriate widths of laps, sizes of rivets, and spacing.

A most important point in hull design is to get continuity of strength throughout the length of the structure. As in a notched bar, any break or sudden change of section causes a concentration of stress. At the steps, therefore, and at all cockpit openings, windows, hatchways, etc., special stiffening must be provided to carry the longitudinal load through. A doubling plate should be provided on the outside to surround any opening completely, and it must be adequately attached to both transverse and longitudinal members. Additional stringers or girders should be built up inside, if the opening is large, and extend at least a whole frame each way beyond the opening. If these precautions are not observed, the concentration of stress will quickly show itself in cracking and buckling of the material in the immediate neighbourhood. The construction of the steps presents particular difficulty. The girder strength must be adequate to compensate for the sudden change of section. Elaborate shaping is unavoidable, and watertightness must be preserved at all corners. The usual solution

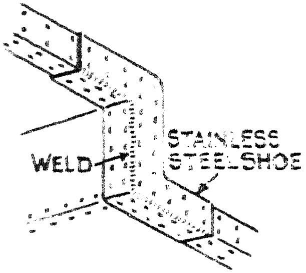


FIG. 259

(By courtesy of "The Aeroplane")

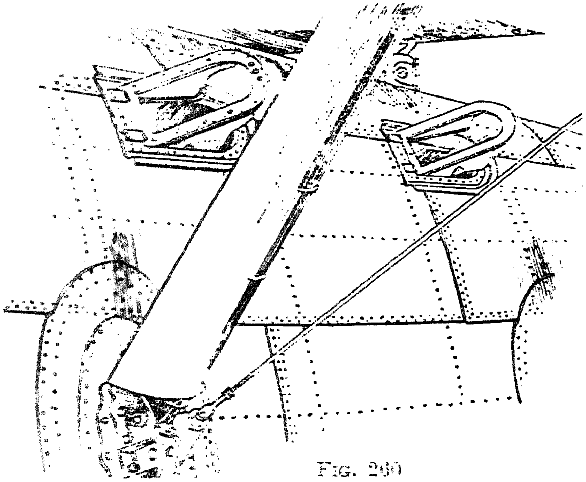


FIG. 260

(By courtesy of "Flight")

is to fit shaped capping pieces over both the keel and chine breaks, made from non-corrodible steel sheet to specifications D.T.D. 60A, 166A, or 171A, and welded up (see Fig. 259). By using welding, thus, it is possible to eliminate the pin point leakage holes which would otherwise occur.

It will be noticed that open sections are used throughout the hull construction. This is most important, as it allows every part to be readily accessible for inspection, and makes the work of building easier by simplifying the riveting. Similarly, frames in the fore body should have their shell flanges to the rear, and those in the aft body to the front so that the bevel which is necessary to accommodate the run of the lines shall be an open one.

The Materials of Hull Construction. The hull, which has been here described, is constructed throughout of duralumin or "Alclad" aluminium alloy. There is, however, a movement towards the use of non-corrodible steel sheet. It has already been used for the underwater skin, in thicknesses a little over half of the corresponding duralumin sizes. This has resulted in a slight increase in weight, but even so it remains less than if wood were used. It would be rash to say that non-corrodible steel will eventually be used throughout the structure, except for flying boats much larger than any which have yet been built. Very thin material would be necessary from considerations of weight, and it would be extremely difficult to make it robust enough to withstand the impact and handling loads of everyday service. Developments on the metallurgical side may be for the equal benefit of both the light alloys and of steel.

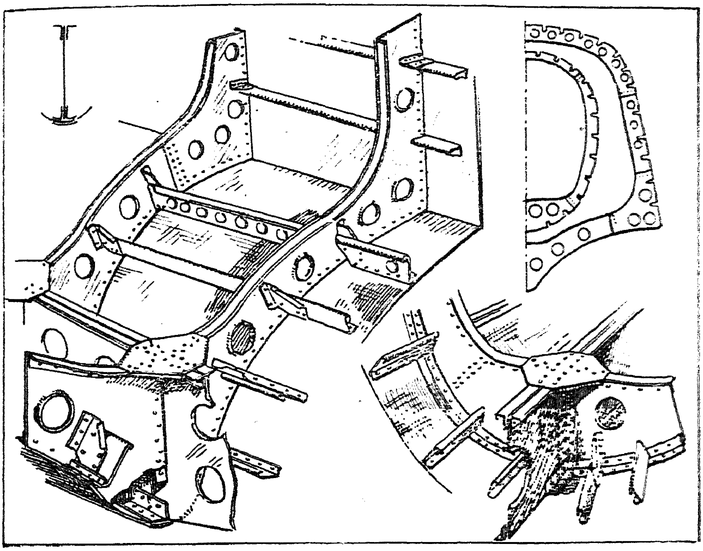


FIG. 260A. HULL OF BLACKBURN "NILE"

(*By courtesy of "Flight"*)

Hull Fittings. Steel fittings taking towing gear, under centre section struts and the tail unit, etc., must be non-corrodible. Since they are likely to be highly stressed, they must be bedded on to sufficiently stiff and large duralumin doubling plates to spread the stress efficiently. These doublings should be in two or more laminations stepped up in size and riveted to the hull skin over frames, which are in themselves specially strengthened. The steel fittings may then be bolted through, with the bolt heads bedding into some stiffening angle inside. Fig. 260 illustrates the under centre section strut fitting of the Supermarine *Southampton*.

Some Examples of Hull Construction. The hypothetical hull just described represents, in general, a typical British design. The hulls actually built by the four leading flying boat manufacturers in this country all have special features, characteristic of the individual designers, which are worth studying.

Blackburn. Fig. 260A illustrates the hull construction of the Blackburn Nile, a fourteen-seater commercial monoplane, 65 ft. long. A most noticeable feature was the use of continuous longitudinal members.

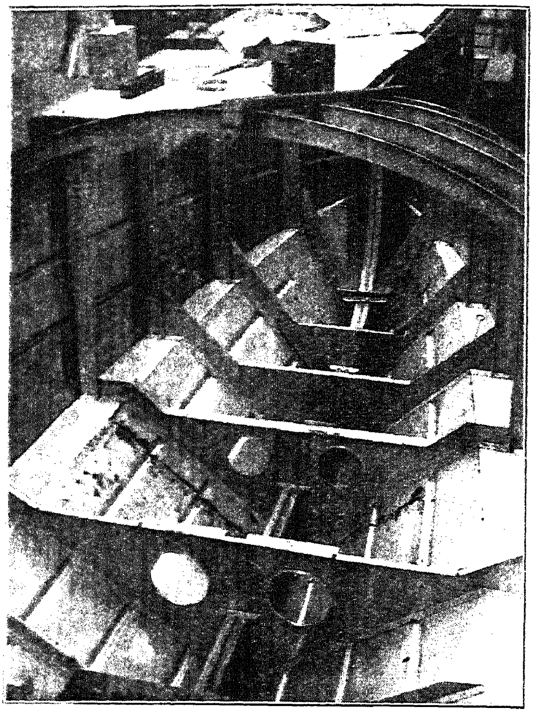


FIG. 261. HULL OF SARO "CUTTY SARK" UNDER CONSTRUCTION
(*By courtesy of Messrs. Saunders-Roe, Ltd.*)

These were drawn from duralumin strip and strongly resembled the bulb angle sections so familiar to shipbuilders. The transverse frames, which were comparatively widely spaced, were notched to allow the stringers to pass through unbroken. Gussets or angle lugs fastened the two together. The centre keelson was, as in most designs, a continuous member, the frames being cut and attached to it by vertical angles and horizontal gussets. The frame webs were cut out from flat sheet, and made in several pieces, riveted together, to prevent undue waste in the large sections. They were edged with continuous boundary angles, both against the shell and on the open inside edge. In this design the keel plate was wide and capped outside with a thick strip, the same width as the bottom keelson angle flanges.

Flanged holes were used liberally wherever possible in the deep web plates to reduce structure weight.

Saunders-Roe. The Saro construction is in several ways a distinct departure from the orthodox. Prolonged trials on a number of commercial types appear to have proved it satisfactorily (see Figs. 261, and 262). In the outward form of the hull straight lines are used wherever possible. The cross sections have no curves, except in the deck camber, and, though the plan side profiles are curved, there is little or no panel beating. A reverse curvature is usual under the chine of most British hulls to throw off the water. In the Saunders-Roe hulls this is replaced by two straight lines, meeting at a very oblique angle.

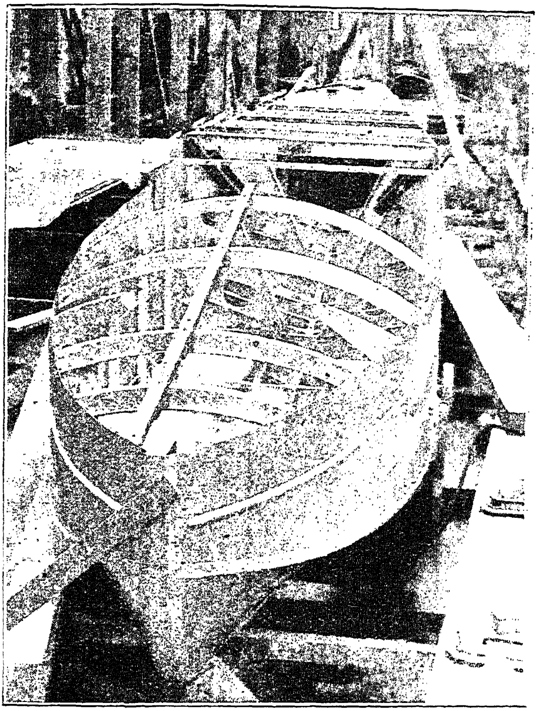


FIG. 262. FORWARD END OF HULL OF SARO "CUTTY SARK"

(By courtesy of Messrs. Saunders-Roe, Ltd.)

The principal feature of the construction is the absence of longitudinal stringers, a direct contrast to the Blackburn and Supermarine hulls. Their place is taken by corrugations pressed in the shell plating. These also serve to stabilize the flat panels against secondary failure and "panting."

The frames, which are closely spaced, are built up from straight edged floor plates with boundary angles, and parallel Z-sections. These open sections are easily accessible, not only for riveting but also for inspection and drying out of moisture.

The keel follows normal practice and is continuous. There is no dorsal, and the only other longitudinal members are the chine and gunwale angles.

"Alclad" alloy is used throughout.

A similar construction is used in the large military flying boat, the Saro *London*, though it is not expected that the external corrugations of the shell will survive into later designs where high performance is of great importance.

Short. The first noticeable feature of the earlier Short boats was that the shell plating was in transverse rings instead of longitudinal strakes (see Fig. 263). These rings were one frame space wide, and were supported by a large number of fore and aft stiffeners (see Fig. 264). In the *Calcutta* type the stiffeners were of a closed V-section running from frame to frame. In the larger and later *Kent* class they were channels or Z-sections, with flanged lightening holes in the webs, and continuity was preserved by gussets at every frame. This would appear to be an improvement, not only in giving greater longitudinal strength, but also in reducing the number of inaccessible places where corrosion might have occurred.

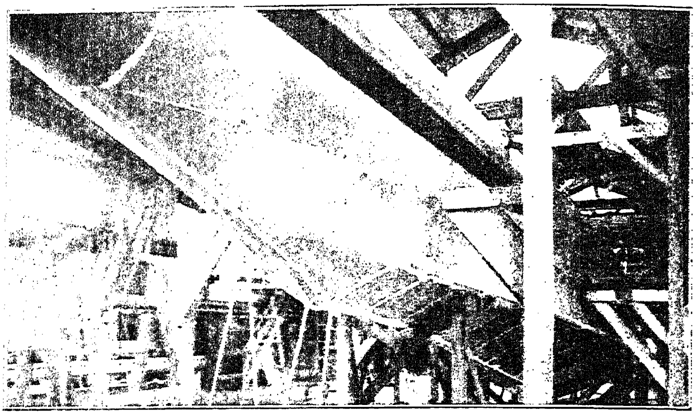


FIG. 263. REAR STEP, SHORT "CALCUTTA" CLASS
By courtesy of Messrs. Short Bros. (Rochester and Bedford), Ltd.)

The upper portion of the frame in the *Calcutta* was a double channel ring with floor plates added to the lower portion to the outer contour of the chine and bottom. The main spar frame and bulkhead of a larger boat is illustrated in Fig. 265. It will be seen that the spar end load was carried through the tube across the face of the frame and independently of it. Even greater longitudinal strength was to be expected where, as in this case, notches were cut to allow the stringers to run through unbroken. Referring again to Fig. 264, the two transverse cargo battens added between each frame will be noticed. These were single channels notched across the stringers to preserve the shell plating from inside damage. They also served to stiffen the stringers against side buckling. An unusual arrangement of rivets will be seen in the

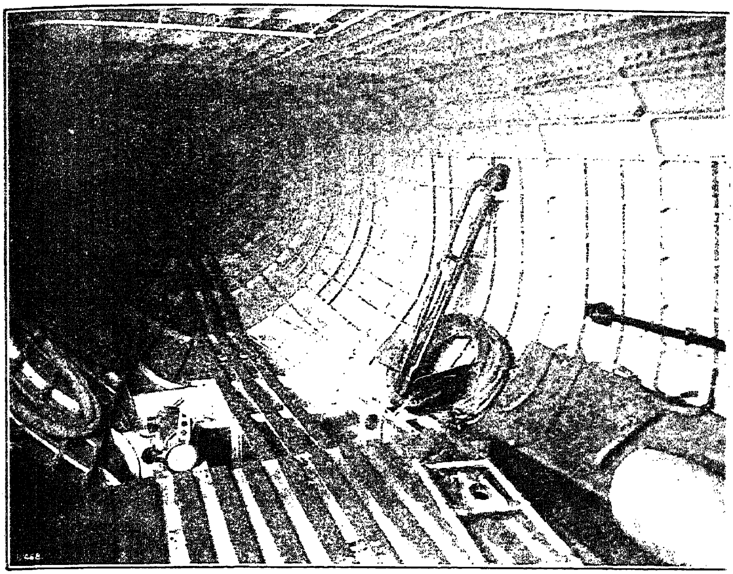


FIG. 264. VIEW LOOKING AFT FROM REAR LUGGAGE COMPARTMENT, SHORT "KENT" CLASS

(By courtesy of Messrs. Short Bros. (Rochester and Bedford), Ltd.)

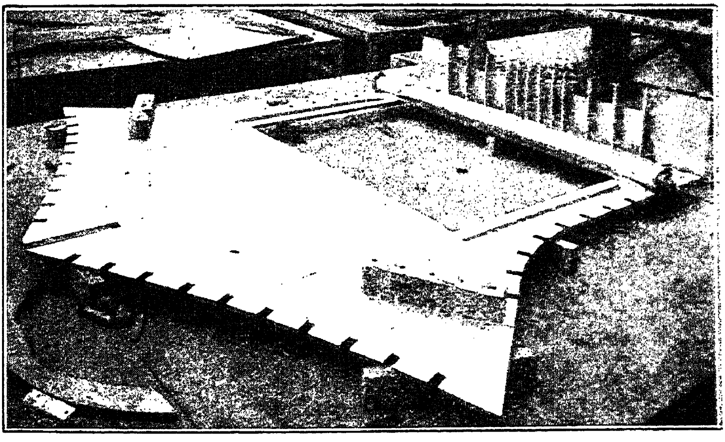


FIG. 265. MAIN SPAR FRAME BULKHEAD, SHORT FLYING BOAT

(By courtesy of Messrs. Short Bros. (Rochester and Bedford), Ltd.)

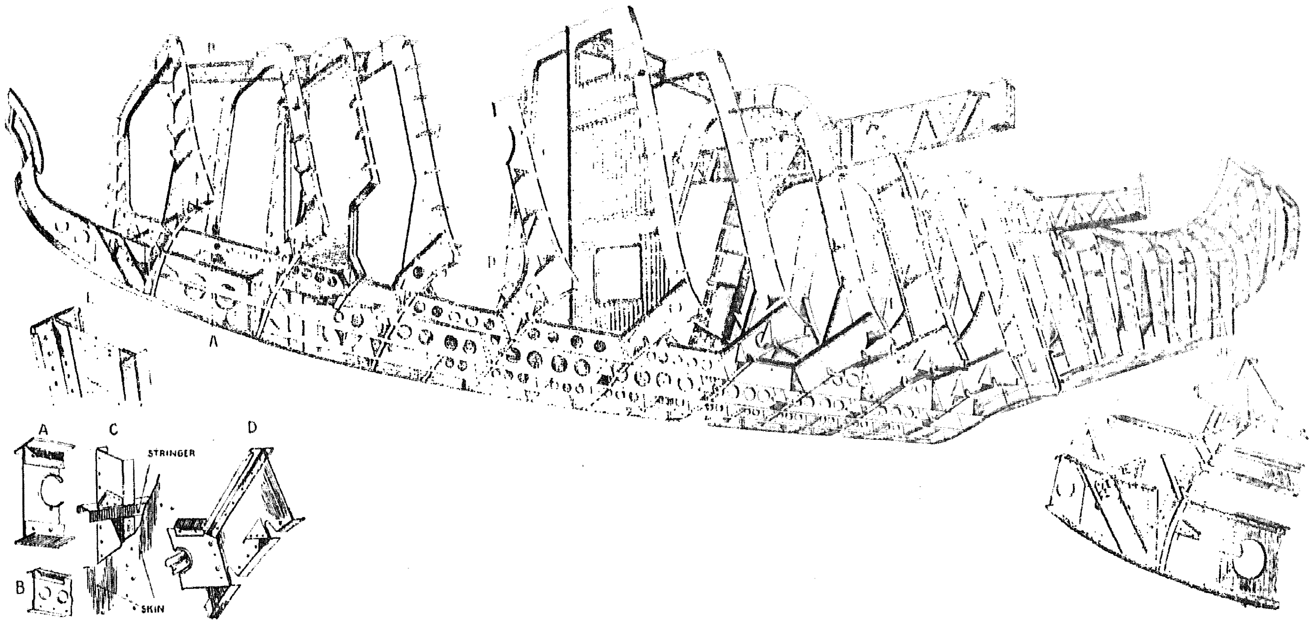

A
A
C
STRINGER
D
B
SKIN

Fig. 266. Supermarine "Scapa" Hull Framing
(By courtesy of "Flight")

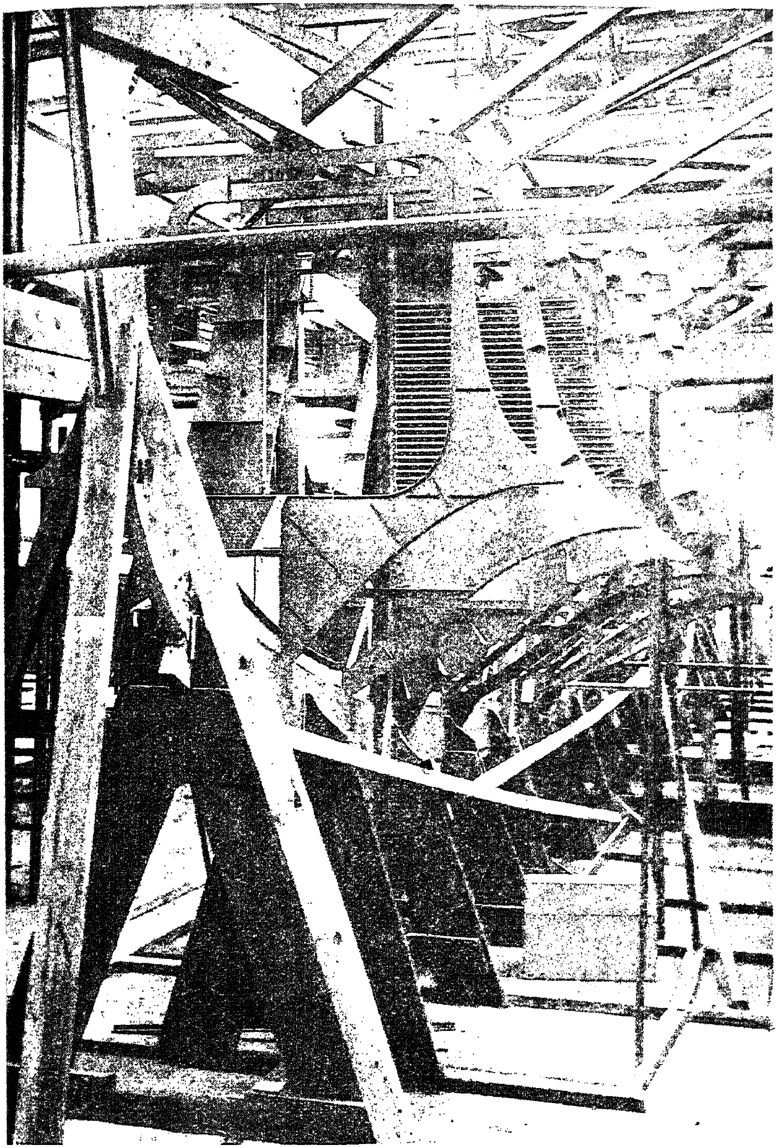


FIG. 267: "STRANRAER" HULL FRAMING

Webs and shell angles of longitudinals are intercostal. Face bars continuous

(By courtesy of Supermarine Aviation Works Ltd.)

shell seams. Double riveting was used, the outer line being very closely pitched for watertightness, the inner line having a rivet opposite every fourth one in the outer. Above the water-line the pitch of the outer line was opened up considerably.

The later and larger [illegible] boats of the Empire and Sunderland types show several marked developments. The outside plating of the hull followed the conventional practice and was laid on in longitudinal strakes. The plate edges were joggled and countersunk riveting was used. The material of the shell plating and of the girders bent up from sheet was Alclad N.A. 23 ST. while the heavier extruded structural members were of Hiduminium R.R. 56.

A feature of this construction is that the frames are continuous and that the stringers are broken at every frame.

Supermarine. Supermarine metal hulls are built on very complete frameworks of both transverse and longitudinal members, to which the shell plating is added in fore and aft strakes.

The topside frames of the *Scapa* are made from parallel flat plate webs cut to the contour with flanged edges or angles riveted on to form a channel section (see Fig. 266(C)).

The floor plate portion of the frame which slopes down from chine to keelson is also of flat sheet, with flanged lightening holes and bounded with plain angles riveted on. A corner gusset is added between the topside and floor portions of the frame.

The centre section spars of the lower plane are built into the hull frames with which they coincide. These frames are particularly heavy (see Fig. 266(E)). The web plate has double angles on both its inner and outer edges. The inner edge is further stiffened with a cover plate having flanged edges. The worst local load which the spar frames have to take are probably those due to alighting when all the weight of the superstructure—main planes and engines—acting downwards meets the impact of the water acting upwards. At all times in flight these frames must transmit the weight of the hull and the tail loads to the main planes, these loads reaching them through the longitudinal members and the shell plating.

In the Supermarine hull there is no lack of longitudinal stiffening. A contour keelson (Fig. 266(A)) and dorsal (Fig. 266(B)) form a girder the length of the hull. In addition, there are continuous angle stringers, the frames being notched out to allow of their passing through. Several of these stringer angles have plate webs added to form deep side keelson girders. The webs are cut at each frame, and a connection made with small angle pieces.

In the *Stranraer* hull (Fig. 267) the stringers were intercostal and notches were not therefore cut in the frames. The shell or "face" angles of the frames were continuous from deck to chine and from chine to keel.

In both the *Scapa* and the *Stranraer*, bulkheads between the compartments were made by plating across the appropriate frames with corrugated sheet. The stiffness of such plating under shear loads has already been discussed on page 29.

FOREIGN DESIGNS. **Boeing.** In the Boeing 314 the centre section of the wing, out as far as the inner mounting engines, is built integral with the hull (see Fig. 268).

The outer sections of the main plane described on page 102 are attached at the outer sides of the inner engine nacelles. This is not only convenient structurally, but it helps in the operation of the aircraft because the centre section of the wing is of such size that it may be used for cargo stowage. It must, therefore, be completely accessible from the inside with the hull. The bulkheads opposite the front and rear spars of the wings are massive braced structures, and the methods used in building them are clearly illustrated in Fig. 269.

The jig lies flat on the floor of the workshop, and has locating pieces for all the structural members, which are of square channel section joined together by ample gusset plates, riveted on. The members are all dropped into position and the gusset plates added. Over the top of the whole jig runs a drilling machine. This is on rails parallel to the top and bottom of the structure and the drill itself moves from top to bottom, and can thus be used systematically to drill all the bolt and rivet holes in the frame. By extending the rails endwise it is possible to use the drill for a second bulkhead in the reverse position.

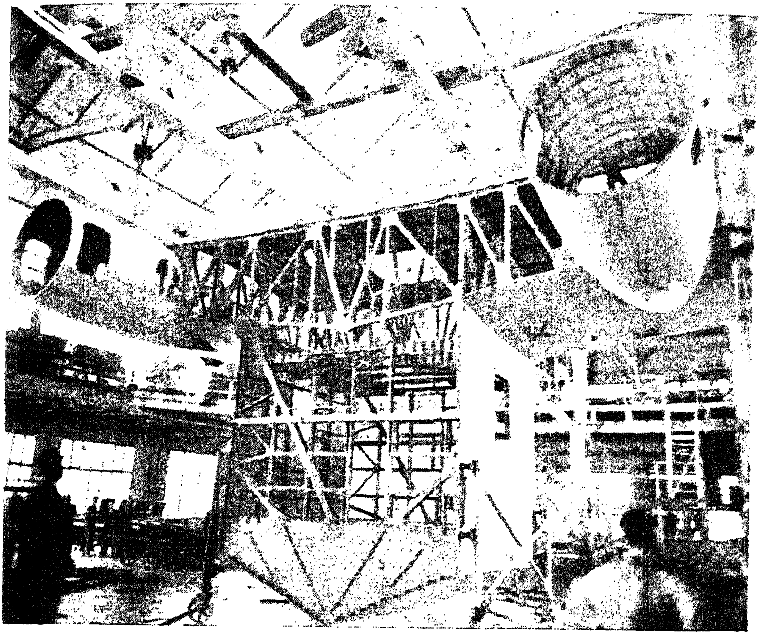


FIG. 268. CENTRE OF BOEING CLIPPER

The central portion of one of Pan-American Airways' six transatlantic Clippers assembled at the Boeing Aircraft Company, Seattle. This photograph shows the portion of the hull which contains the dining saloon and above it, the centre section of the wing structure which is used for cargo space. On the outer ends of the section are the two inner engine nacelles, which incidentally stand 25 ft. above the assembly floor. All four engine nacelles are accessible during flight by way of wing companion-ways

(*By courtesy of the Boeing Aircraft Company*)

It will be seen that the cross-sections of the hull are entirely straight lines, thus limiting double curvature and expensive panel beating. An intermediate bulkhead is seen in Fig. 270.

This shows how the portion beneath the cabin floor level is subdivided into watertight compartments. Wherever such a watertight bulkhead occurs the longitudinal stringers are broken, the connection across the bulkhead being made by small angles riveted thereto. This is a much simpler method than running the stringers through unbroken and trying to put watertight joints round them. This illustration shows

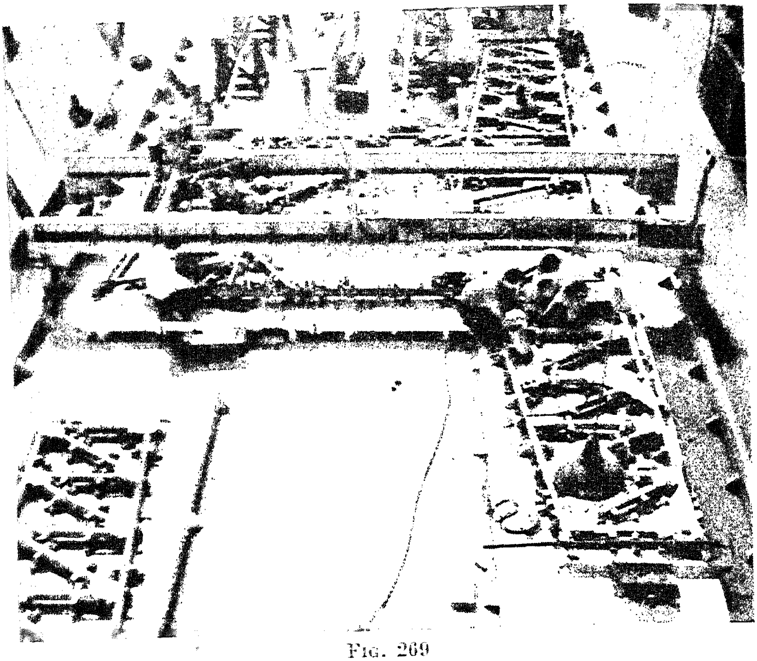


FIG. 269

Assembly of one of the centre section bulkheads, built partly of steel and partly of duralumin alloy, used on Pan-American Atlantic-type Clippers. The left part of the photograph is framework for the hull; to the right is the centre section of the wing spar. A massive "drill jig" rolling on rails over the entire layout to facilitate accurate construction

(By courtesy of the Boeing Aircraft Company)

the joint plates which project sideways to carry the stub wings used on the Boeing 314 to give transverse stability. From the upper stub wing connection a stout girder runs downwards towards the centre, transmitting the stub wing loads to the bulkhead structure. The upper portion of the bulkhead above the cabin floor level does not need to be watertight, and is very strongly braced. It is an open structure, having a doorway running through it.

Consolidated Aircraft Corporation. This company has produced a very successful range of flying boats which are largely used by the U.S. Navy.

The structural methods are characteristic of the best modern practice. The hull form is a little unusual in that the depth is relatively small by comparison with the beam. This results in it having a flattened ovoid

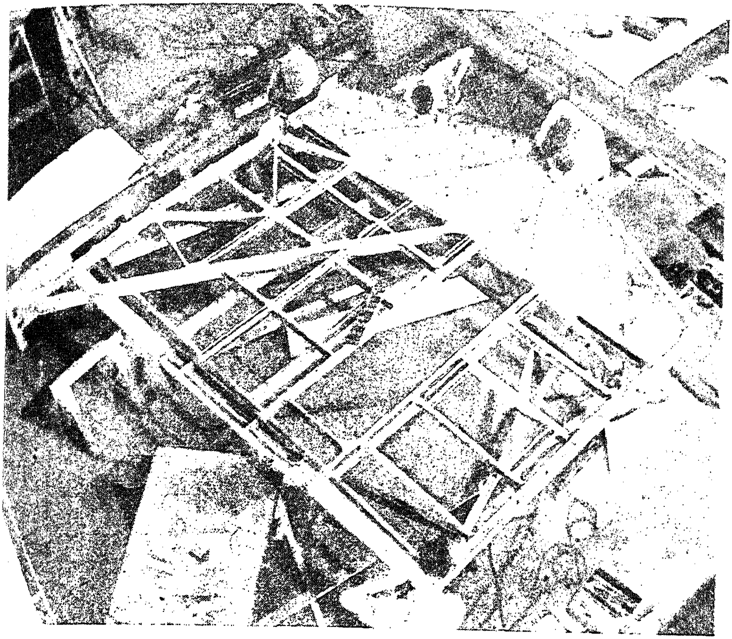


FIG. 270

Assembly of one of the centre-section bulkheads for a Boeing 314 Pan-American Clipper. It is constructed of both steel and aluminium alloy, fitted together with rivets and bolts. A series of watertight compartments run along the bottom of the hull.

(*By courtesy of the Boeing Aircraft Company*)

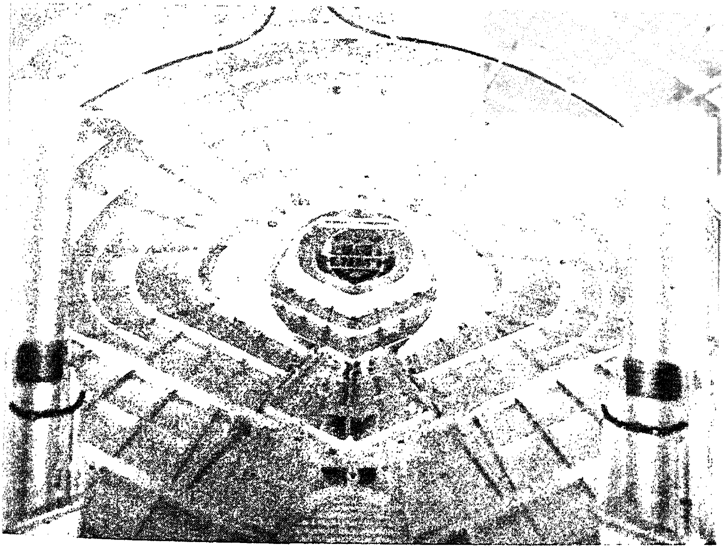


FIG. 271. CONSOLIDATED FLYING BOAT HULL

(*Official U.S. Navy photograph*)

section, the planing bottom portion of which is straight, at least in the afterbody (see Fig. 271).

Forward of the main step the flat V planing bottom is flared to meet the chine line horizontally.

Strong transverse bulkheads are fitted at intervals, but the stringers run through longitudinally in unbroken lengths. Between each bulkhead a number of light frames are built in. These consist of a continuous hoop of channel or Z-section run across the free flanges of the stringers. In between the stringers a web piece continues down to the shell covering and is riveted to it.

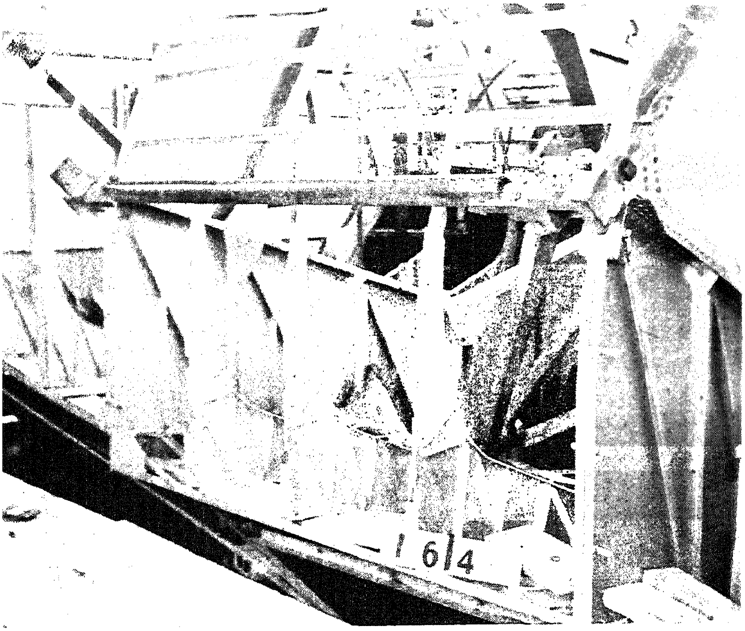


FIG. 272. CONSOLIDATED HULL CONSTRUCTION

(*By courtesy of the Consolidated Aircraft Corporation*)

The construction of the afterbody and of the portion of the hull in the immediate neighbourhood of the main step is shown in Figs. 271 and 272.

Dornier. The Dornier construction appears to derive much less from shipbuilding practice than the British types just considered. This is particularly evident in the *Wal* (see Figs. 274 and 275). In the 1933 model of this machine, however, the flat bottom, which was characteristic of earlier years, was dropped and replaced by a V-bottom flared into the chine, giving the cross section of the boat a shape similar to that used generally elsewhere. The frame consisted of a heavy plate or lattice girder across the bottom of the boat with light channel side and deck members. The webs of these channels had closely spaced lightening holes for the better prevention of corrosion.

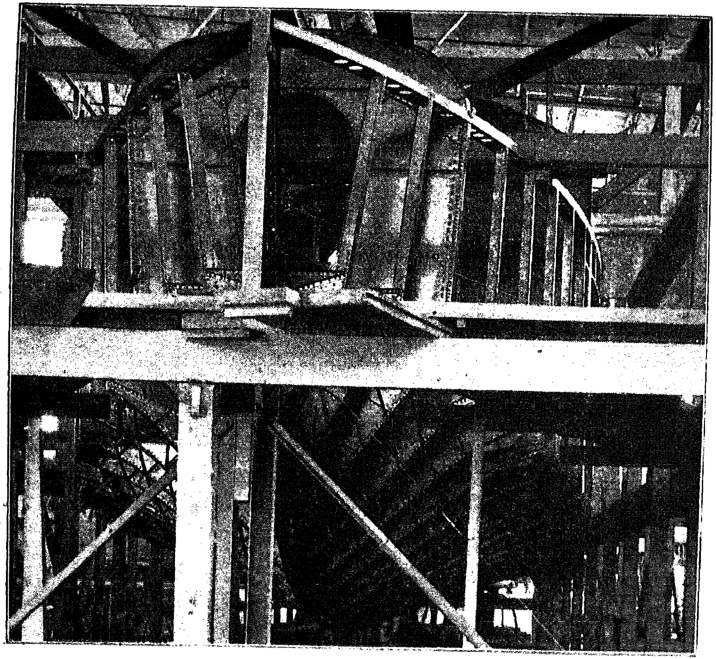


FIG. 273. FRAMING OF SIKORSKY S.40 AMPHIBIAN FLYING BOAT

(By courtesy of the Sikorsky Aviation Corporation)

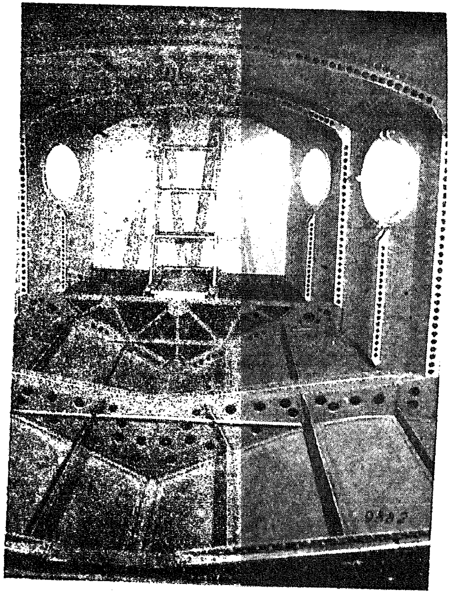


FIG. 274. DORNIER "WAL"—HULL STRUCTURE INSIDE CABIN

(By courtesy of Dornier Metallbauten G.m.b.H.)

In the heavier frames, such as those occurring at the stubs, the frame was well braced against shear distortion by tubular ties (see Fig. 275).

Fig. 274 shows the internal structure in the passenger cabin of the *Wal*. This portion was entirely free from cross bracing and simplified

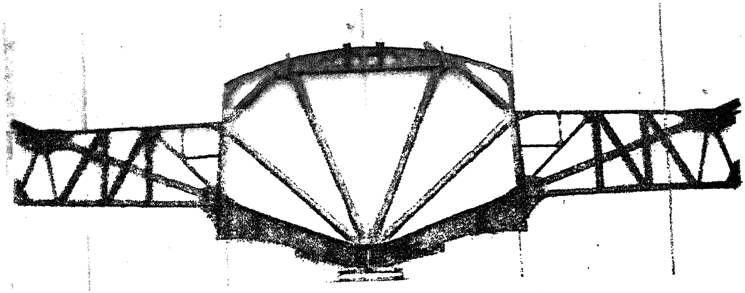


Fig. 275. Dornier "Wal"—Main Frame

(By courtesy of Dornier Metallbauten G.m.b.H.)

the fitting of the passenger accommodation. The frames were widel spaced, but there were intermediate side stiffeners between them. N

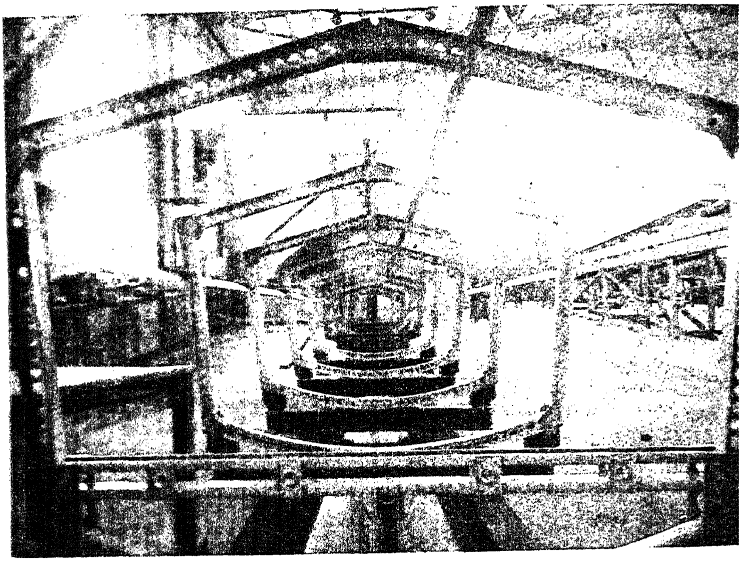


Fig. 276. Dornier "Wal"—Hull Framing

(By courtesy of Dornier Metallbauten G.m.b.H.)

keelson was used, but the planning bottom was well supported with intercostal angles attached to each frame. Further longitudinal strength was provided by the chine and gunwale. The side plating was in two strakes

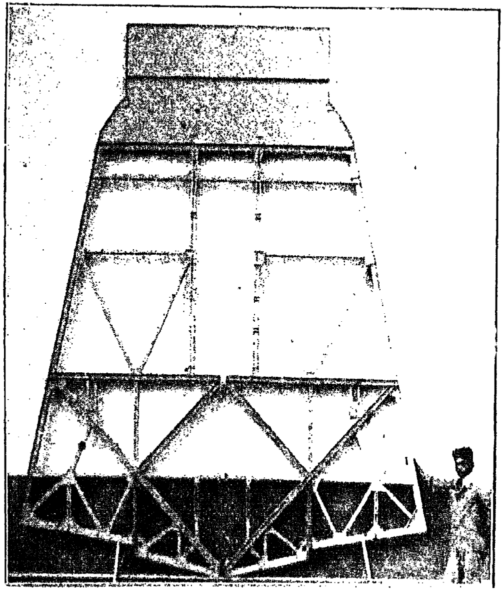


FIG. 277. MAIN FRAME OF LARGE DORNIER HULL

(By courtesy of Dornier Metallbauten G.m.b.H.)

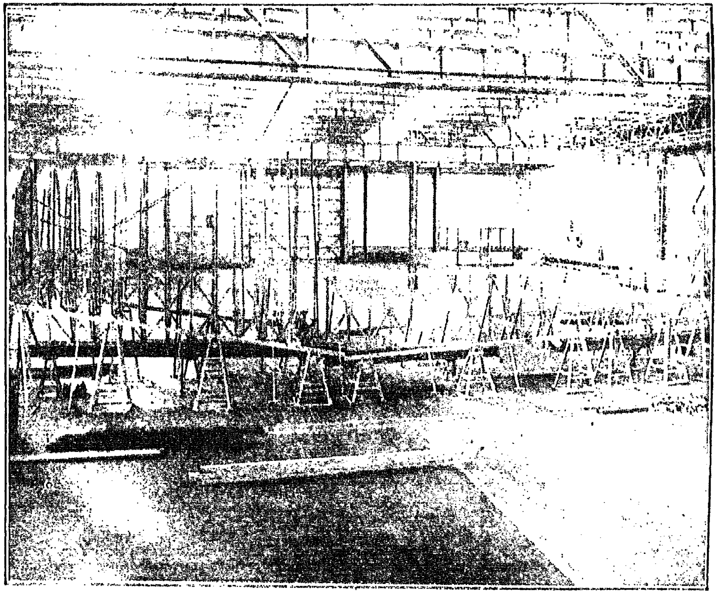


FIG. 278. CENTRE KEELSON GIRDER OF LARGE DORNIER HULL

(By courtesy of Dornier Metallbauten G.m.b.H.)

with a double-riveted lap joint. Torsional strength was given by watertight bulkheads from keel to deck level. These, of course, also served to subdivide the boat into watertight compartments.

Although the smaller Dornier boats are without a centre keelson, the large ones have a deep braced girder from end to end in addition to the shallow longitudinal steps on each side (see Figs. 277 and 278). The frames are braced structures built on to each side of the centre girder.

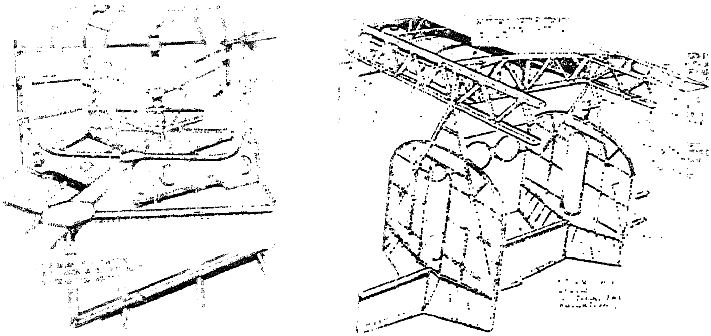


FIG. 279 FIG. 280

SIKORSKY S-42A HULL CONSTRUCTION

(*By courtesy of "The Aeroplane"*)

The frame construction resembles that of the *Wal*, but the much greater size has led to a different line diagram.

The stabilizing stubs, which are so characteristic a feature of Dornier boats, do not form part of the hull structure but are attached externally. One of the stub spars is shown in Fig. 275.

Very complete weight figures of various Dornier hulls were given in *The Journal of the Royal Aeronautical Society*, No. 216, Vol. XXXIII, December, 1928.

Sikorsky. The Sikorsky Aviation Corporation of Bridgeport, Conn., have developed a very successful series of amphibians and flying boats. In the earlier amphibians, such as the S40, the hull was a self-contained unit, to which was attached externally a flying structure, consisting of main planes, engines and tail unit, the latter being supported on booms off the main plane and hull.

The hull was of aluminium alloy construction throughout, with an "Alclad" skin. It was anodically treated and painted to prevent corrosion.

A plate girder keelson ran from stem to stern, and to it the frames were attached in halves each side. The keelson boundary angles were extruded sections, riveted back to back through the web, which was stiffened with extruded angles. The frames consisted of a floor plate with boundary angles from keelson to chine and a straight extruded angle section from chine to gunwale. The gunwale was an extruded Z-section. Certain of the frames were built up as watertight bulkheads of plating stiffened with angles.

Side keelsons of extruded bulb angle section ran fore and aft from frame to frame, and were riveted to frames, bulkheads, and plating. The only stressed structure above the gunwale was a built-up arch which formed the rear partition of the pilot's compartment and which carried the wing bracing and landing chassis struts. The deck was supported on extruded angle and Z-section beams. Cabin inter-window verticals and longitudinal stringers were of Z-section.

The shell plating was riveted to frames and stringers, the joints being

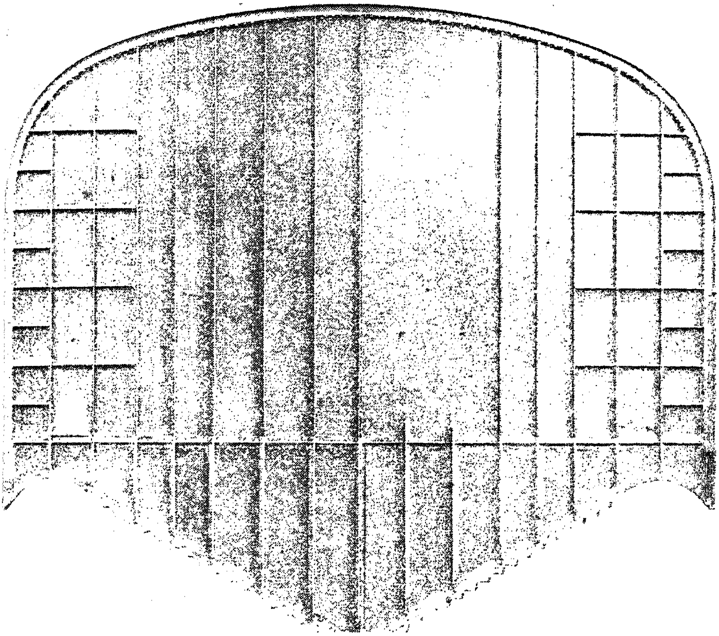


FIG. 281
MARTIN "CHINA CLIPPER" BULKHEAD
(By courtesy of the Glenn L. Martin Co.)

made watertight with cotton tape impregnated with marine glue. This construction is illustrated in Fig. 273. The S-42A, was a big step forward in flying boat design. The monoplane wing is mounted at the centre on extensions of the two main hull bulkheads and at the mid-point of each semi-span on lift struts running down to the chine (see Fig. 280).

The hull construction is very similar to that of the earlier S-40 but several improvements in detail have been made. One of these may be seen in Fig. 279. The side keelsons consist of extruded Z-sections and the transverse floor plates run across the tops of these, which simplifies manufacture and assembly. The bilge water in each compartment can run through and be mopped up or pumped out more easily. It will not collect at each frame causing numerous points of corrosive attack.

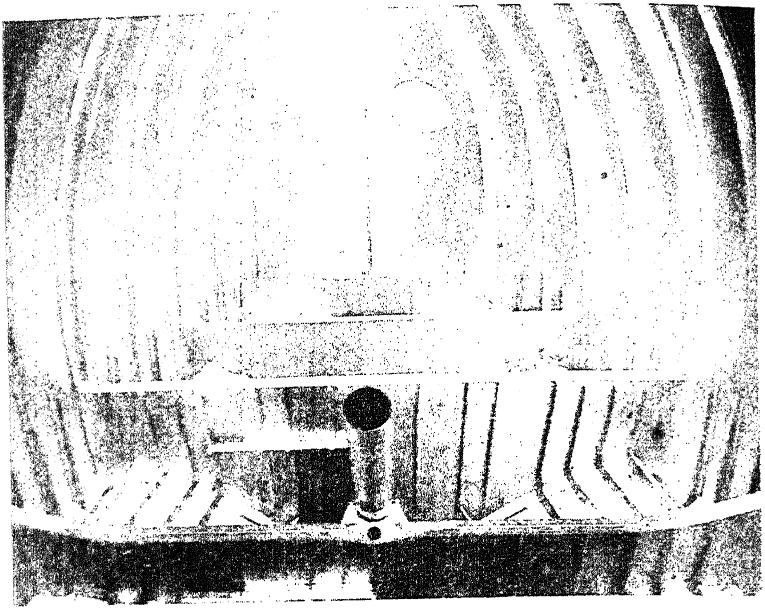


FIG. 282
(By courtesy of the Glenn L. Martin Co.)

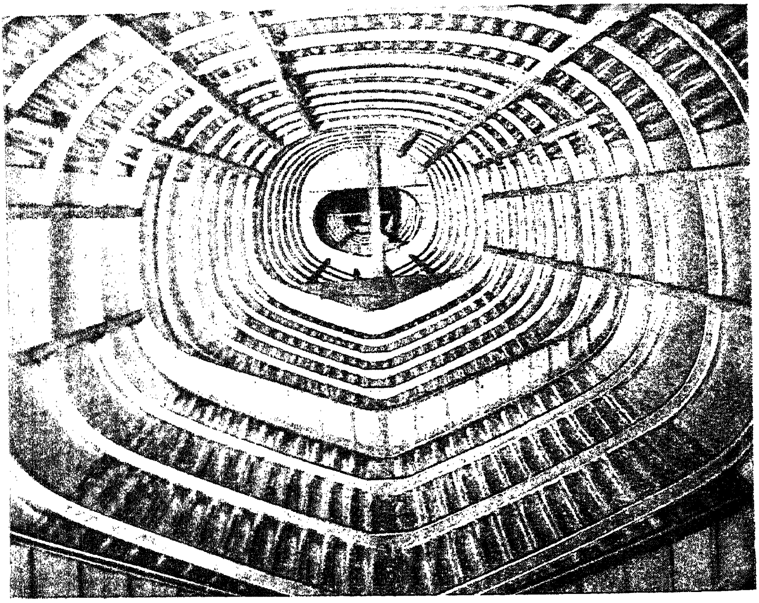


FIG. 283
MARTIN "CHINA CLIPPER" HULL CONSTRUCTION
(By courtesy of the Glenn L. Martin Co.)

Glenn L. Martin. The constructional methods used for flying boat hulls by Glenn L. Martin help to illustrate the fact that hull construction throughout the world is much more standardized than any other part of the aeroplane. The photographs (see Figs. 284 and 285) show the interior of a Glenn L. Martin boat and one of the main bulkheads. The hull section presents the best modern features in a sharp V bottom with a reverse curve to the chine, and flat sides running into a cambered deck. A strong keelson and dorsal are continuous throughout the length of the boat. Longitudinal strength and shell stiffening is provided by a number of closely-spaced side keelsons along the planing bottom inside the skin. In the ordinary frames there is a deep floor plate, the free edge of which is stiffened with double angles. A channel runs down the

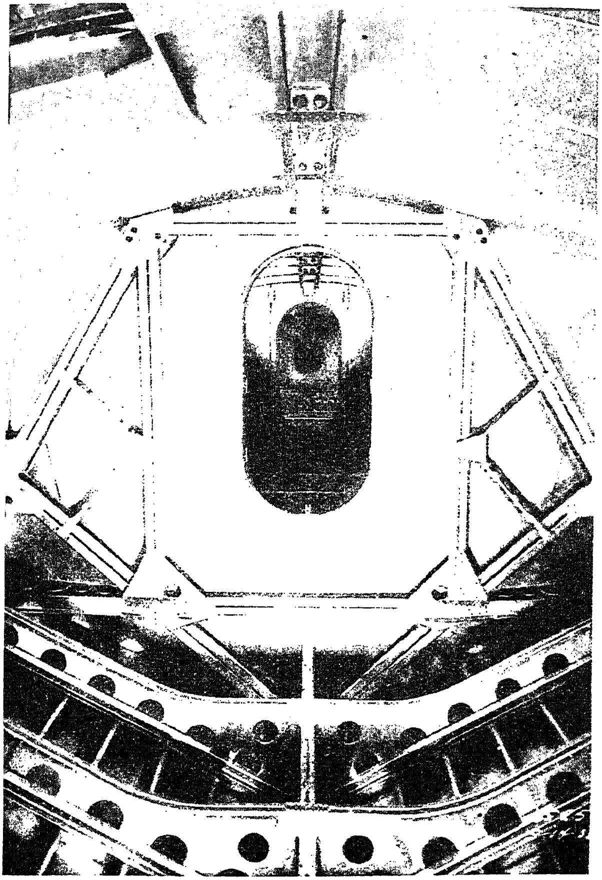
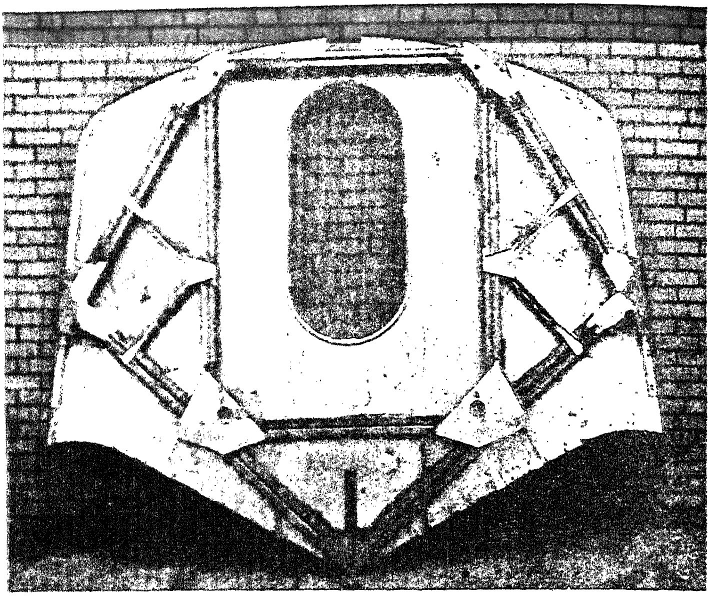


FIG. 284. GLENN L. MARTIN—HULL STRUCTURE

(*By courtesy of the Glenn L. Martin Co.*)

floor plates on each side, parallel to the planing bottom and across the top of the side keelsons, to each of which there is a single riveted attachment. The main bulkhead frame (Fig. 285) is made up of three plates with vertical single riveted lap joints. As this bulkhead carries, at its sides, the lift strut attachments, it is very strongly reinforced with double channels forming a framed structure with large riveted gussets



Glenn L. Martin—Main Bulkhead

(By courtesy of the Glenn L. Martin Co.)

at each joint. The bulkhead door opening is well stiffened round its edge with a riveted beading. There is a boundary angle round the edge of the bulkhead, wide and double-riveted up the side, narrow and single-riveted round the gunwale and deck.

Special methods have been developed for the much larger and more modern China Clipper built by this company for Pan-American Airways. As in monocoque fuselages the top and bottom of the rear end of the flying boat hull must take large bending stresses. In the China Clipper, these are catered for by corrugated sheet which, of course, has a much higher buckling strength than flat sheet and moreover it removes the necessity for stringers. The longitudinals appearing in Fig. 28[illegible]) are merely wooden ribands used in the assembly. On the sides of the hull only flat sheeting is used. At the forward end of this hull (see Fig. 282) the floor is specially strengthened to take the water loads in taxying and alighting. The floor frames are exceptionally deep and also act as partial watertight bulkheads. The planing bottom is stiffened by closely spaced intercostal stringers of

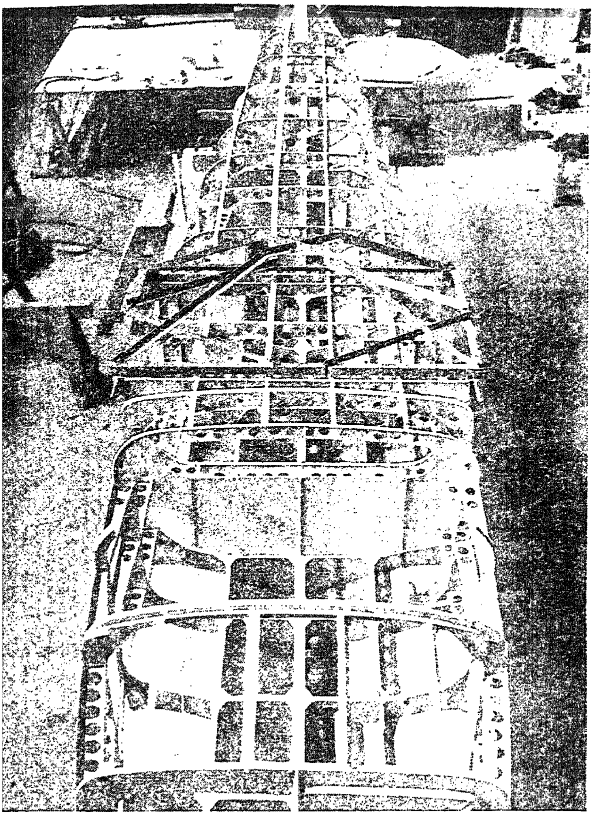


FIG. 286. C.A.M.S. 90—HULL FRAMING
(By courtesy of Chantiers Aéro-Maritimes de la Seine)

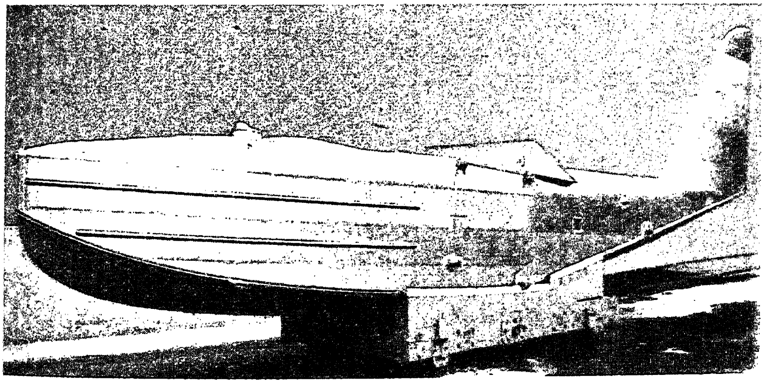


FIG. 287. C.A.M.S. 90—SHELL PLATING
(By courtesy of Chantiers Aéro-Maritimes de la Seine)

building shop and templates or moulds made to the frame sections. Each frame should be templated in parts to represent its components—the floor plate, the side member, the deck beam, the deck and chine corner brackets, the outside contour being taken from the scrive board and the remaining information from the drawings. It should then be possible to lay each template on a piece of sheet of the appropriate thickness and to transfer all the particulars on to it for cutting and shaping.

When only one machine is being built the templates may be in thin

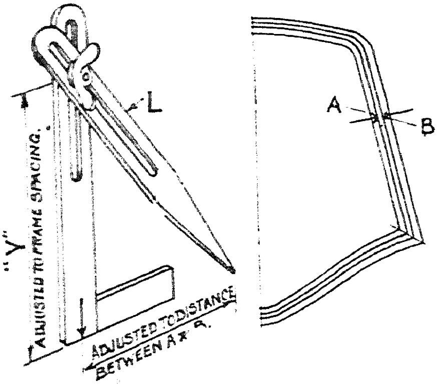

L
"Y"
ADJUSTED TO FRAME SPACING.
ADJUSTED TO DISTANCE BETWEEN A & B.
A
B

FIG. 290

(By courtesy of "The Aeroplane")

wood, giving no more than the outside contour of the finished frame. But when working on a production basis it is advisable to have the templates in sheet steel of, say, 18 s.w.g. carrying full information down to the positions of rivet holes. Such templates may then be clamped to the sheet metal and used as drilling jigs. Fig. 289 shows one of the bulkhead frames of a modern Short boat laid on the setting-out table for checking against the lines.

A further wooden mould, $\frac{3}{4}$ in. to 1 in. thick, may be made from the scrive board to each frame contour, round which the shell flange angle of the frame may be bent to its correct contour.

Reference to Fig. 257 shows that in the particular design given, these contour lines are for the most part straight. When the hull is designed in this way, with the deck camber, the radius of the deck corner brackets, and the flare under the chine as constants throughout most of the length, the number of moulds is much reduced and the construction made cheaper and simpler at every stage. Nor is it apparent in practice that such hulls are less efficient either in the air or on the water. At this stage the bevelling of the frame shell flanges to follow the fore and aft run of the boat should be done. For this it is necessary to turn to the scrive board again and to use a bevel measurer of the type shown in Fig. 290.

Supposing that the bevel of the frame flange at *B* is required. The arrow mark on the bevel measurer is applied to a point *A* opposite to *B* on the next frame contour on the scrive board. The adjustable distance Y is made equal to the frame spacing, and the point of the movable leg L is brought up to B. The angle between L and the vertical leg of the bevel measurer gives the required bevel. Since the bevel, particularly on the frames at the ends of the boat, is likely to vary considerably between dorsal and keel, the bevel measurer should be used at four or five positions on every frame.

Templates should be made in the mould loft for the keel and dorsal contours. These will serve two purposes, first for making the keel and dorsal, and second for making the contour moulds in which they are erected (see Fig. 291). This contour mould should be set up and shored in the actual position in which the boat is to be built, under cover and with a convenient run-way to lift the hull when complete on to a trolley for removal. The keel and dorsal plates may then be built into it complete, their top and bottom flange angles added and the whole riveted together. In the meantime the frames should have been prepared in complete half units (port and starboard) on the bench and be ready to erect on to the keel and dorsal.

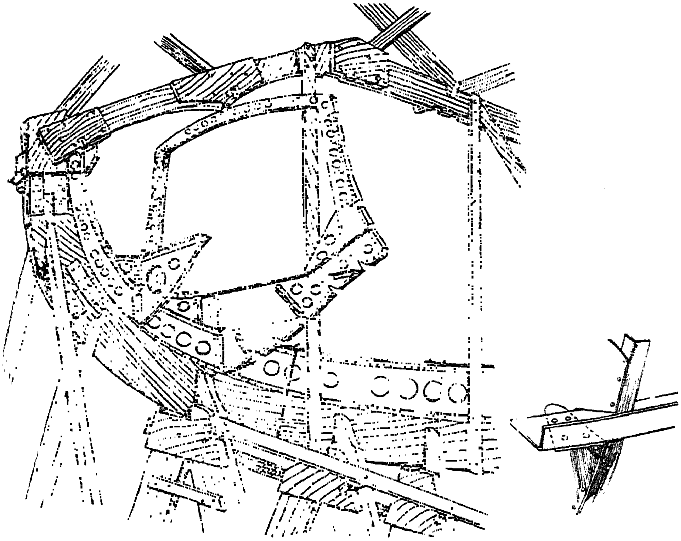


FIG. 291

(*By courtesy of "Flight"*)

A constant watch must be kept by the shipwrights on the fairness of the hull as the work proceeds. Distortion in the longitudinal direction is likely to occur as the various weights are added. The verticality and straightness of the profile mould should be checked all along its length each day and any sagging corrected at once. In the same way, the frames must be checked before they are finally riveted up. Until the stringers are actually riveted in the structure, ribands will be necessary to support the frames. These should take the form of pitch pine battens running the length of the boat and clipped to every frame. There should be one within one or two inches of the eventual position of each continuous stringer. As will be seen from Fig. 292, the rigidity of the frame to riband attachment depends on the tightness of the bolt. If the frame distorts fore and aft, the bolt may be slackened off slightly, the frame tapped back into position, and the bolt tightened again. It is usual in shipbuilding to lay off the ribands carefully in the mould loft before they are actually required, and to mark on them the exact position of each frame.

The importance of a day-to-day inspection of the hull for local distortion or sagging cannot be overestimated. If, for instance, a shell plate has been templated from a structure which has fallen out of truth, the plate must be either scrapped or an unfair line expected in the finished boat. And the unfairness becomes all the more evident when covered by a smooth sheet of plating.

When the frames are finally riveted up they are ready for the positions of stringer angles and plate edges to be marked on. These are transferred from the loft floor to scrive board by means of flexible laths girthing the frames. The lines must be faired in by clipping light battens along the frame marks from end to end of the boat and adjusting them until they are satisfactory. The only thing which can ensure real fairness in these lines is the eye of an experienced shipwright. Fair lines having been obtained, the true and final positions of stringers and plate edges on the frames are known, and the stringer notches may be cut. Once the keelsons and side girders are built in, the shell plating may be begun. Since the hull is "clinker built"—that is, with the lower edge of each strake of plating as the sight edge (except for the keel)—the first strakes to be put on are the garboard ones. Until such time as the plating is nearly completed and the profile mould can be cut away, the keel plate cannot be added. It is the last thing riveted on before painting the inside.

The plating is continued strake by strake. Each plate is first cut to shape, this being picked up, if necessary, by means of a template from the framing. It is then beaten or rolled to fit the contour and temporarily clipped into position. The run of frames and stringers can now be marked on and the plate taken down for drilling. This operation of temporary erection may be dispensed with if the templates are made more elaborate, an expense well justified on "production" work.

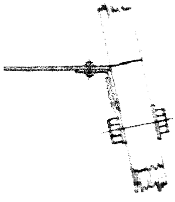


FIG. 292

(By courtesy of "The Aeroplane")

The rivet holes having been drilled, the plate is re-erected and acts as a drilling jig for the frames and stringers. If heat treatment and anodic treatment have to be carried out, they should precede this erection. As the holes in the frames and stringers are drilled, service bolts are put into every fourth one with washers under to protect the anodic film. To rivet up each plate as it is erected leads to distortion of the framework. For this reason and also to distribute the work more economically it is advisable to leave the riveting until most of the shell plating is bolted into position. Riveting is dealt with in Chapter IX.

It is during the shaping and fitting of the shell plating that most of the defects of designing a hull with elaborate flares and curves show themselves. In the first cutting of the plate, "sny" (a concave edge to the plate) may be found. This is difficult to allow for and not simple to cut exactly, besides putting up the percentage of scrap. Again, in the shaping it is much easier to roll to single curvature than to beat to convexity. Panel beating is particularly difficult in duralumin, and even when the material is annealed repeatedly it is liable to crack under hammering. The metal must be heat-treated either when rolled or beaten, but rolling calls for no annealing if it can be done during the soft phase. When the shell plating is completed there remains little to be done to the hull except the addition of cockpit coamings, fittings, towing rings, etc., all of which are straightforward and call for no particular comment.

As is the rule in most aircraft works, all workmen engaged in or on the machine should wear plimsoles. Even so, the anodic surface of the metal is liable to wear very thin in places which are being constantly walked on.

The hull is now ready for painting and weighing before being handed over to the riggers for assembly with the main planes, engine, tail and control units. All the main attachment fittings for these parts, even when in steel, should have been erected before the boat leaves its building berth. Subsequent drilling and riveting is both uneconomical and unsatisfactory.

SUMMARY OF PROCESSES. The various processes through which each piece of duralumin sheet or angle passes on its way from store to final erection are as follows—

1. Cutting out the blank in its flat developed form.
2. Annealing to 360° C. or heat treatment to 480° C., depending on the amount of work to be done in the shaping.
3. Rolling, beating or drawing to shape. Punching of flanged lightening holes.
4. If the article has been annealed, then heat treatment must follow here.
5. After heat treatment some slight re-shaping may be necessary, but it must be done quickly before age hardening sets in.
6. The article should now be anodically treated and greased with lanoline. This operation may not be necessary if "Alclad" alloy is used. Each small item must be treated separately before riveting into assemblies, however small these may be.
7. The unit is ready for erection or riveting into some assembly, which in its turn is erected into the boat.

FLOAT CONSTRUCTION

The design and construction of floats, whether as the undercarriage of a seaplane or as the transverse stabilizers of a flying boat, follows the principles already laid down for hull construction.

The general practice is to provide a strong fore-and-aft girder in the form of a keelson and dorsal, on to which are built the transverse frames, in halves each side. The plating is in longitudinal strakes. There is usually one step amidships, and the after body tapers to a vertical edge at the stern. In racing craft the keelson and dorsal may be combined in one longitudinal bulkhead from top to bottom and end to end of the float. The length of the float may be divided into four or five watertight compartments by bulkheads mounted on the appropriate frame angles with a close spacing of rivets. Strong points must be provided for the chassis struts, and the attachment fittings should be mounted on a robust structure locally with large doubling plates to distribute the load.

In general, marine aircraft of over 8,000 lb. all-up weight have been built as flying boats, and the float seaplane type has been less than that weight. It is difficult to quote typical scantlings owing to the scarcity of data and the special considerations which have influenced individual designs.

A reserve buoyancy of 100 per cent is usually provided on military and commercial types, and each float in the standard twin float arrangement therefore has a displacement equal to the all-up weight of the whole machine. Average scantlings for the duralumin or "Alclad" alloy floats of a machine weighing 4,000 lb. all-up may be taken as follows—

Shell plating . .	18 s.w.g. sides and topsides tapering to 20 s.w.g. aft: 16 s.w.g. bottom tapering to 18 s.w.g. at ends.
Centre line bulkhead .	20 s.w.g. with 1½ in. × 1½ in. × 18 s.w.g. boundary angles, both sides;
or	
Keelson and dorsal of similar weight and strength.	
Side keelson if provided	1½ in. × ⅝ in. × 18 s.w.g. angles, cut at each frame.
Chine angles	1½ in. × 1½ in. × 18 s.w.g. angles.
Side stringers	1 in. × ⅝ in. × 20 s.w.g. angles.
Transverse fra	12 in. to 18 in. apart. Floor plate 20 s.w.g. with ¾ in. flange at top and to shell. Hoop from chine to dorsal of 1½ in. × ⅝ in. × 20 s.w.g. channel or Z-section. Bulkheads, 20 s.w.g. plate.

A point of difficulty in float construction is the provision of access to the interior for holding up the rivets in the last strake of plating put on. A typical solution of this problem is seen in the Fairey float (Fig. 293). The top centre strake has flanged up edges and the edge riveting to the strakes on each side is completely external. In a case like this the frame rivets may be held up from under the end if the length of each plate in the strake is short. But the riveting of the last plate in the strake can only be achieved by providing a screw-down watertight handhole for the purpose. Such handholes are useful afterwards for inspection and drying out.

A full scale experiment was carried out by Messrs. Short Bros., Ltd., in the building of the *Valetta*, a marine aircraft of 22,500 lb. weight in the form of a float seaplane. It appears to show that even in such large sizes the type is not necessarily less efficient than the flying boat. The float construction together with attachment fittings is shown in Fig. 294. They have found[1] that, for floats with 100 per cent reserve buoyancy, the total float weight including chassis supporting points may be taken as 10 per cent of the all-up weight of the machine. In the large types, such as their *Valetta*, this may be reduced to 8 per cent. The linear dimensions of similar floats vary as the cube root of the displacement and the surface area as (displacement)$^{\frac{2}{3}}$.[1]

Although aluminium alloys have been most extensively used for float

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[1] A. Gouge, B.Sc., F.R.Ae.S., "Some Aspects of the Design of Sea-going Aircraft," *Royal Aeronautical Society Journal*, May, 1931. See also *Seaplane Float and Hull Design*, by the Author. (Pitman.)

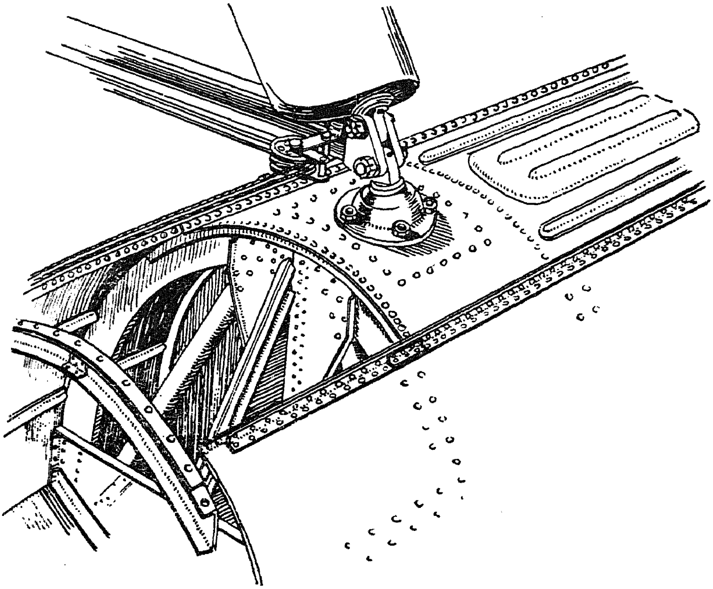


FIG. 293. FAIREY FLOAT CONSTRUCTION
(*By courtesy of "Flight"*)

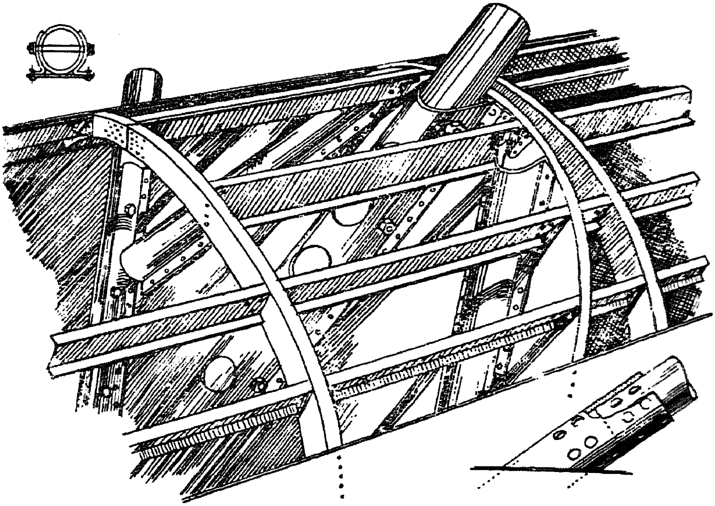


FIG. 294. SHORT "VALETTA" FLOAT
(*By courtesy of "Flight"*)

construction, there is some argument in favour of stainless steel. Its non-corrodible quality allows the constructor to dispense with protective treatments which may be both expensive and heavy. Experimental steel floats have been built by both Armstrong-Whitworth and Short. An example of the former, as fitted to an *Atlas* military biplane, is shown in Figs. 295 and 296.

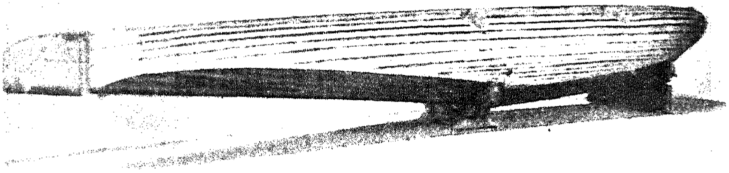


FIG. 295. ARMSTRONG-WHITWORTH "ATLAS"—STAINLESS STEEL FLOAT

(By courtesy of the A.T.S. Co., Ltd.)

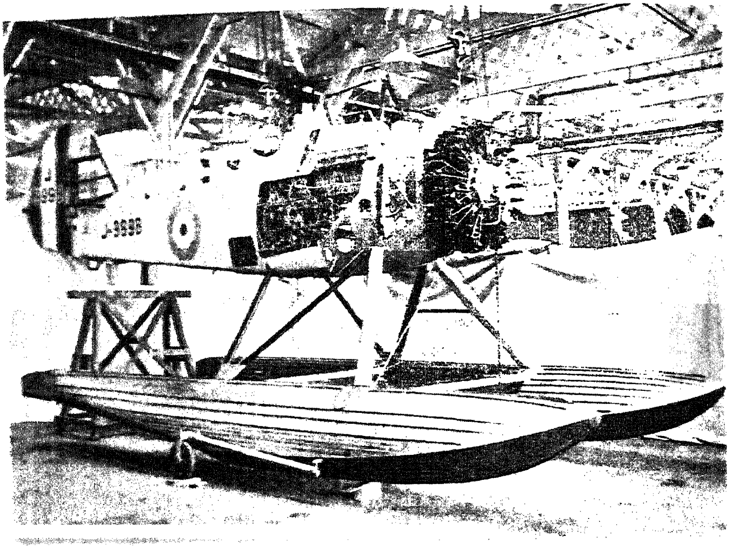


FIG. 296. ARMSTRONG-WHITWORTH "ATLAS"—FLOAT STRUCTURE

(By courtesy of the A.T.S. Co., Ltd.)

Against the saving of protective treatments, however, stainless steel is still an expensive material in itself, and must be used in very thin gauges if the weight is to be reasonable. The *Atlas* floats were 13 per cent heavier than the corresponding duralumin floats, but they are lighter than wooden floats of the same size, particularly if water soakage is taken into account.

The actual material used is the austenitic steel, Specification D.T.D.

166. The shell is laid on in long fore-and-aft strakes with the edges flanged outwards to allow external riveting of the seams. These riveting flanges further serve to stiffen the shell against panting, which is particularly likely to be troublesome owing to the thinness of the sheet. Experiments are being made in welding this material electrically (see p. 374) and if the stress on the welds can be kept sufficiently low to prevent fatigue failure there is considerable promise in the method.

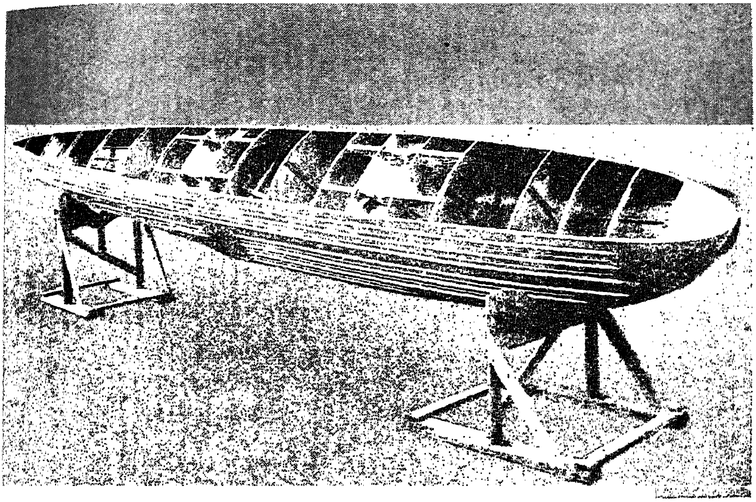
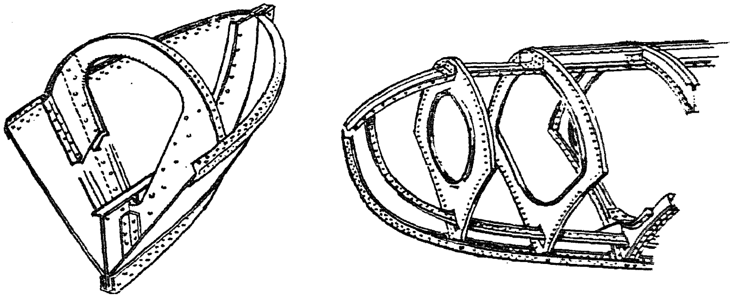


FIG. 297. STAINLESS STEEL FLOAT, SHOT WELDED

(By courtesy of Short Bros. (Rochester and Bedford) Ltd.)



SARO WING FLOAT

SUPERMARINE WING FLOAT

FIG. 298

(By courtesy of "Flight")

The riveting of floats and hulls is a large item of workshop expense and the electrical spot welding process saves both time and material.

A shot welded stainless steel float made by Messrs. Short Bros. Ltd. is illustrated in Fig. 297.

The external strutting of the *Atlas* float structure is of stainless steel streamline tubes. Both front and rear panels are wire braced against the racking loads which occur in taxying across rough water or in alighting with a slight angle of heel. The side panels are braced with diagonal struts which take the float drag and carry the moment due to the longitudinal shift of the Centre of Buoyancy.

The Air Ministry now lays down a method of stressing float structures, and this is described in A.P.970 for military aircraft and in A.P. 1208, Design Leaflet B10 for civil work.

The construction of wing tip stabilizing floats for flying boats can be rather lighter than that of similar size main floats for seaplanes, since they do not have to stand the same impact loads on alighting. The principal difficulty lies in making the attachments sufficiently robust and in distributing the load throughout the length of the float. Subdivision of the float into watertight compartments must be carried out, and it is usual to provide at least two bulkheads. The loss of buoyancy in a wing float may have a very serious effect on the stability of the flying boat as a whole. The internal construction of Saro and Supermarine wing floats is illustrated in Fig. 298.

CHAPTER VI

SUBSIDIARY STRUCTURES

The Tail Unit

In its simplest form, the tail unit consists of two surfaces, one vertical on the centre line of the machine, and one horizontal. They are of a symmetrical aerofoil section, and each is divided into two parts, the front part being fixed and the rear in the form of an operated flap to give directional control. Refinements and additions have been made to this simplest conception of the tail unit.

In large aircraft the vertical may be divided into double or treble fins and rudders. Many recent military designs have shown a cantilever tail plane and elevator with two fins and rudders set well out from the centre line to allow a clear line of fire aft. Though it may appear to be straying into aerodynamics, which is not the subject of this book, it should be stated here that when outboard vertical surfaces are fitted to a multi-engined machine, they should be arranged in the slipstreams of the outer engines. In order to avoid a large span tail plane and the excessive loads which would be associated with it, the engines may be set at a slight angle to the centre line of the machine so that the slipstreams converge on the tail unit. The slipstream has a considerable influence on tail unit design. In a single-engined aircraft the fin is often set at a slight angle to the vertical centre line to balance the engine torque. A further effect of the slipstream rotation is to cause a torsion load in the tail unit as a whole and in particular an unsymmetrical loading laterally on the tail plane and elevator.

The stressing requirements of the Air Ministry are very completely stated in Air Publication 970. Before, however, approaching the structural problems involved in tail unit design, it would be well to consider the air loads which must be catered for.

The tail plane and elevator are taken first as one surface for the purpose of determining the distribution of loading and position of the Centre of Pressure. The worst case is usually that of the down-load in nose diving, but this varies to an up-load in normal slow flight. The distribution and magnitudes of the loads having been determined, the amount carried by each spar may be found. It is usual to provide the tail plane with two spars, the front one of which may be swept back or even form the leading edge (see Figs. 299 and 300). The elevator has normally one spar, which should be made continuous or rigidly jointed at the centre, even though the surface be divided by the rudder. In an unbalanced or partially balanced elevator this spar is subject to torsion due to the cantilevering of the elevator ribs to the rear of it.

The whole elevator load is transferred by the hinges to the rear tail plane spar. This spar or both tail plane spars may be supported off the fuselage by bracing wires or struts. When struts are used they may be attached on the underside of the tail plane, but when wires are fitted on both sides the fin post or posts are brought in to complete the structure and act as compression members.

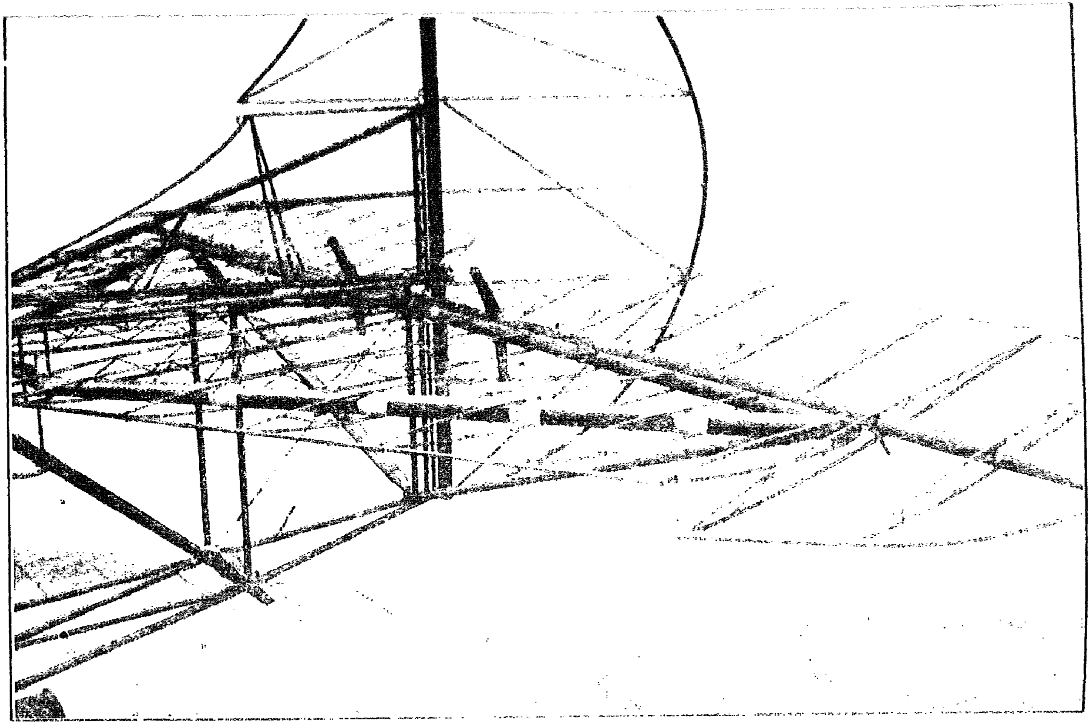


FIG. 299. FRAMEWORK OF FOKKER WELDED TAIL UNIT

(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

The fin and rudder carry similar loads and are treated in a similar way to the horizontal surfaces. The fin posts are cantilevers off the top of the fuselage, and the rear one also takes the rudder loads at the hinge points. Owing to the comparatively small number of ribs, the air load cannot be taken as evenly distributed along the spars. It should be considered as applied at the rib points.

Everything that has been said of aileron design in Chapter III applies equally well to the rudder and elevator control surfaces, particularly in regard to the main torsion member and the attachment thereto of the ribs.

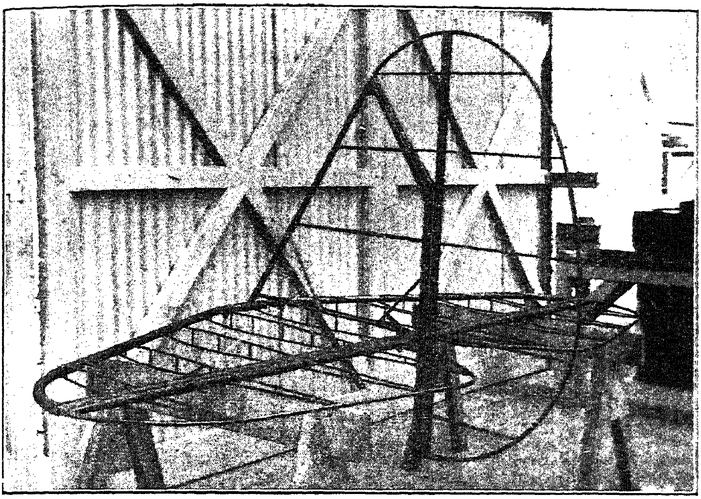


FIG. 300. SKELETON TAIL UNIT OF SEGRAVE "METEOR"
(By courtesy of Messrs. Saunders-Roe, Ltd.)

Turning now to the structural design, it is found that tail units may be built in as diverse ways as main planes or fuselages. They may be welded up from mild steel tube. Again, some designers favour high tensile steel strip, others duralumin tube and drawn duralumin strip. The decision is influenced by the methods and materials employed elsewhere on the machine. Thus, mild steel tube, welded, is used by Fokker and drawn steel strip by Hawker. When drawn strip, either steel or duralumin, is the material, it is possible to construct the tail unit of sections already designed for the main planes or fuselage, a most economical procedure.

The Fokker tail (Fig. 299) is an interesting example of welded construction. Except for the spars, the sections are all small, thin-walled tubes. They call for nimble handling by the welder, but make a light and neat job when finished. It will be noticed that where the ribs cross the front tail plane spar, the spar tube is sleeved, so that the welding does not touch it directly. The fact that the spars are not parallel is, of course, sufficient to lock the sleeves in position. Although the rear tail plane spar is double braced, tubes are used for the lower members, a desirable feature in view of the damage which wires would sustain on a rough aerodrome. The side load from the fin passes through the upper bracing wires. The rear spar, therefore, carries end load from three sources, the upper and lower bracings being two, and the third that induced by drag on the swept back front spar.

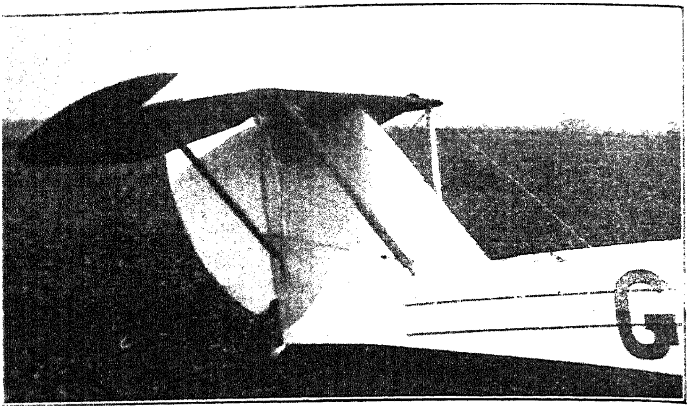


FIG. 301. TAIL UNIT OF SARO "CUTTY SARK" AMPHIBIAN FLYING BOAT

(By courtesy of Messrs. Saunders-Roe, Ltd.)

A small point to be noticed is that the upper bracing wires are attached to the tail plane spar by a lug which is situated on the rear side of the spar. Thus the offset creates a torque in the spar to balance that caused by the elevator load, applied through the hinges, in the worst down load nose-diving case.

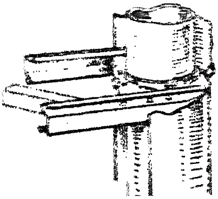


FIG. 302

(By courtesy of "Flight")

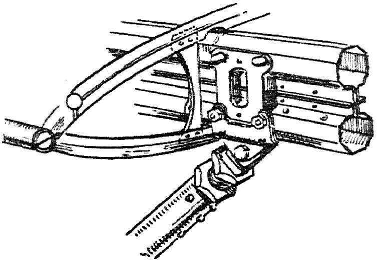


FIG. 303

(By courtesy of "Flight")

A similar type of structure was that used by Saunders-Roe in the Segrave *Meteor* (Fig. 300). In this case the front spar formed the leading edge of the tail plane. A further example from the same firm is illustrated in Fig. 301, the tail unit of the Saro *Cutty Sark*, an amphibian flying boat. A welded mild steel structure proves quite satisfactory for marine work if adequately cadmium-coated. Drain holes must, of course be provided at the lowest point of the rudder. In this case the fin was built of "Alclad" alloy, integral with the hull. When the tail plane is adjustable, care must be taken in designing the bracing attachments so that there shall be no binding. In the *Cutty Sark* the rear edges of the tail plane move about a hinge at the front spar. The external bracing wires were, therefore, taken only to the top ends of the front struts, which were fixed. The rear struts rise and fall, being fastened at their lower ends to a king post, working in slides with the adjustment.

It might be thought that the welded type of tail unit would be heavier than one of drawn strip, pinned or riveted. Weights quoted by Mr. A. A. Gassner, late Chief Engineer of the Fokker Aircraft Corporation, of America,[1] show that in three different designs the tail unit weighed between 1·3 and 1·57 per cent of the all-up weight. In this country it has been found possible to fulfil the requirements of the Air Ministry at less than 1 lb. per square foot of surface, including bracings.

When a drawn strip structure is used, it follows closely the methods already outlined in Chapter III for main planes and in particular ailerons. That this is so will be seen in Fig. 302 of the Gloster *Goldfinch* and in Fig. 303, a typical Hawker tail plane spar with rib and bracing attachment.

Pressings are also frequently used in tail unit construction, and the examples given in Figs. 304 and 305 come from the Curtiss *Carrier Pigeon II*. The rear fin spar is a pressed channel with circular lightening holes, and the ribs are also pressings similar to those used on the Curtiss main planes (see p. 60). The front spar and diagonal bracings are tubes.

The mechanism seen in front of the rear spar is the elevator kingpost, which slides at its top end to allow for the tail adjustment. The king-post is formed of two tubes, and at the slide is attached a fitting to take the top ends of the external tail plane bracing wires. The rudder hinges, which are webbed stampings, are fastened to the rear fin spar, opposite ribs in each case.

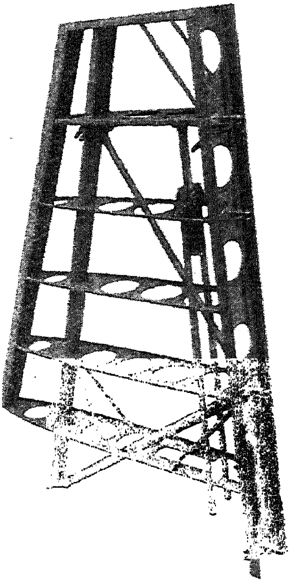


FIG. 304. CURTISS "CARRIER PIGEON II"—FIN

(*By courtesy of the Curtiss Aeroplane & Motor Co., Inc.*)

The tail plane and elevator of the *Carrier Pigeon* follow the same principles as the fin. The elevator spar is a channel section, and since this is unsatisfactory in taking torsion, it is braced with triangles run back and having their apices on ribs; these members are all pressings. The tail plane, which has two spars, is braced with tubular drag members and crossed wires.

The Sikorsky S-40 tail unit, shown in Fig. 306, has a number of features of considerable interest. The whole construction is of duralumin

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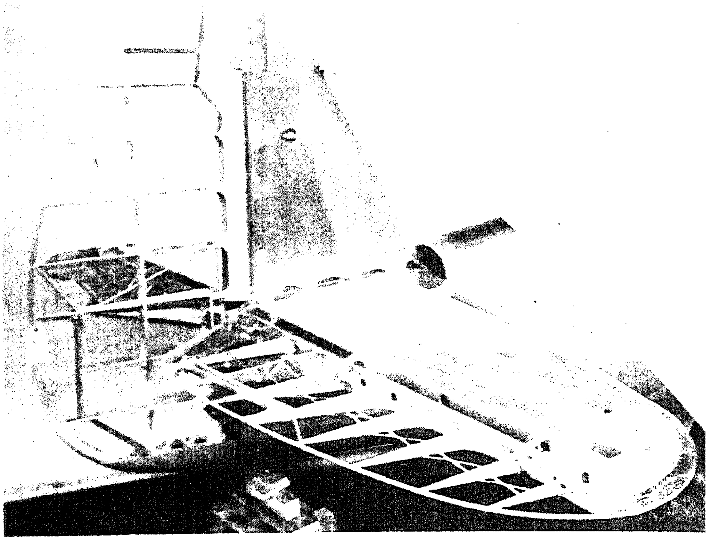
[1] *Aviation*, October, 1930.

An important point in the design of tail units is to allow for ease of assembly and maintenance. In this example (see Fig. 309) the tail plane is first assembled on the fuselage, the fin being mounted on top of it and bolted through the strong centre rib of the tail plane. The skin covering is divided into a number of small pieces, the end piece where the double curvature is at a maximum being pressed in one. The remainder is covered with narrow strakes running out from the centre towards the tip. The moving surfaces, i.e. the fin and elevators, have D-section leading edges to which are attached pressed aluminium alloy ribs running back to a tubular trailing edge to which they are attached by tubular rivets. In order to prevent the ribs pulling over during the attachment of the fabric, they are supported by flat strips which run from end to end at the mid-chord.



309. CURTISS "HAWK 75" TAIL UNIT

(By courtesy of the Curtiss-Wright Corporation)

The hinges between the moving and fixed surfaces of the tail unit are frequently eyebolts, with or without ball bearings. The fixed surface may have a double eyebolt and the moving surface a single one which fits between the double lugs of the former. To meet the requirements of assembly and interchangeability the gap in the double lug eyebolts may be made oversize, and shims or washers inserted at one of the hinges to locate the moving surface along the direction of the hinge axis. This ensures that any loads in that direction are applied at only one point and not distributed in an indeterminate way between them all. One of the two eyebolts in each hinge must be locked against rotation which might jam control movement.

When ball-bearing hinges are used the bearing should be pressed into the single lug eyebolt, and one of the hinge pins fitted with distance pieces so that it can be clamped up tight on the inner race. This will prevent movement of the pin and wear in the holes. The pin should be of as large diameter as possible irrespective of the calculated loads, and even on a light aeroplane it should not be less than ¼ in. diameter.

Where ball bearings are not used the holes in the eyebolts should be bushed so as to simplify the maintenance. Such holes invariably wear, even though large diameter pins are used. It is then frequently difficult to replace the bolts as this may mean opening up the interior of the structure. If, however, bushes are used they may be pressed out and replaced quickly.[1]

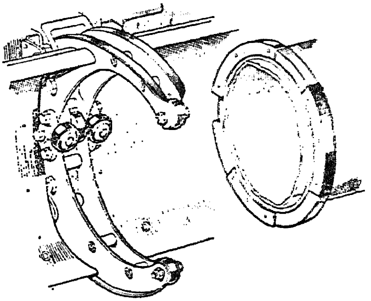


FIG. 310
(*By courtesy of "Flight"*)

In the Vickers *Wellington* an unusual hinge was used.

The elevator tube itself ran on ball bearings mounted in a double horseshoe on the tail plane spar, as shown in Fig. 310.

The Tail Skid or Wheel

Although the tail skid is actually a part of the undercarriage, its design must be done in conjunction with the tail unit when, as is frequently the case, it forms part of that unit structurally. The Air Ministry requirements for tail skids have been stiffened up considerably, for, though the skid is of no importance when in the air, its failure on the ground may lead to serious damage to the adjacent parts. A reserve factor of 4 is required on the vertical load which the skid carries. This must also be combined with an horizontal drag load equal to half the vertical one. There may also be a considerable torsion applied to the radius member when the skid tracks over on a rough-surfaced aerodrome.

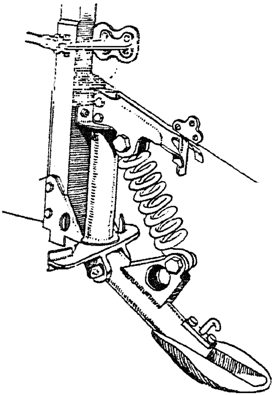


FIG. 311
(*By courtesy of "The Aeroplane"*)

The de Havilland tail skid (Fig. 311) is typical of many used on light aeroplanes. It is of the tracking type and is operated indirectly through the rudder controls. The skid pan is an iron casting bolted to the radius member. Many materials have been tried for pans, including hard tool steels. They have not, however, shown themselves in any way superior to cast iron, which can be replaced very cheaply when worn out. Bulk of metal at the points of wear and abrasion is an advantage, but there is, of course, no reason for carrying any surplus elsewhere.

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[1] Suitable limits and tolerances for hinge pins, ball-race hinges and eyebolt gaps are given in the *Handbook of Aeronautics*, Chapter 3, on "Construction."

In this example the compression member is a helical steel spring. Stops are provided to prevent too great a rotation.

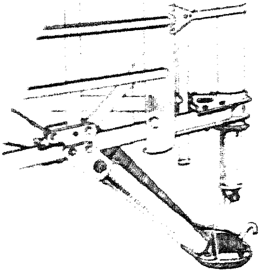

FIG. 312

(By courtesy of "The Aeroplane")

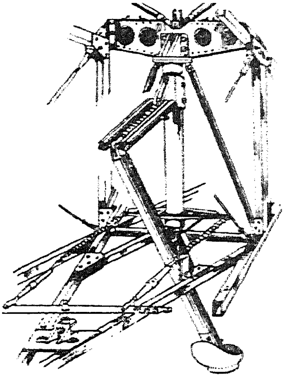

FIG. 313

(By courtesy of "The Aeroplane")

The small hook for lifting the rear end of the machine will be d. It is most useful when man-handling with the aid of a tail trolley. Refinements of this type of skid for larger aircraft include the fitting of a cage or guide for the compression spring, and also a rebound spring inside the main one. On larger machines it becomes possible to use an oleo instead of springs. Figs. 312 and 313 show two other types of tail skid, as used on the Blackburn *Bluebird* and Westland *Wapiti* respectively.

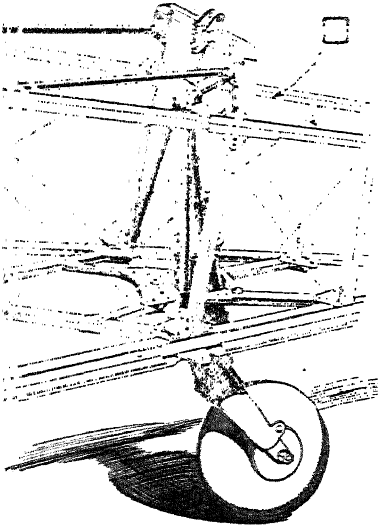

FIG. 314. WESTLAND WALLACE TAIL WHEEL

(By courtesy of "Flight")

The use of wheel brakes on the main undercarriage allows of a different kind of skid, in the form of a wheel. Previously, the friction of the skid on the ground was to a great extent relied on to pull up an aeroplane on landing. The use of a small wheel is now increasingly popular on machines with braked under-carriages, the brakes providing the deceleration.

The Westland *Wallace* is fitted with a tail wheel of the type shown in Fig. 314. The wheel is free to castor, and the vertical hinge runs up to a braced joint in the plane of the top longerons.

The stiffening of the fuselage to take the tail wheel loads has been thoroughly carried out. The vertical reaction passes up the main sprung member to be met at the top by a stout cross girder and two tubular ties which brace it back to the fuselage side panels. The Air Ministry requires a factor of $4\frac{1}{2}$ on the attachment and mounting of the tail wheel. This, associated with a factor of 4 on the wheel fork and strut ensures that in the event of breakage, the fuselage will have additional strength in hand.

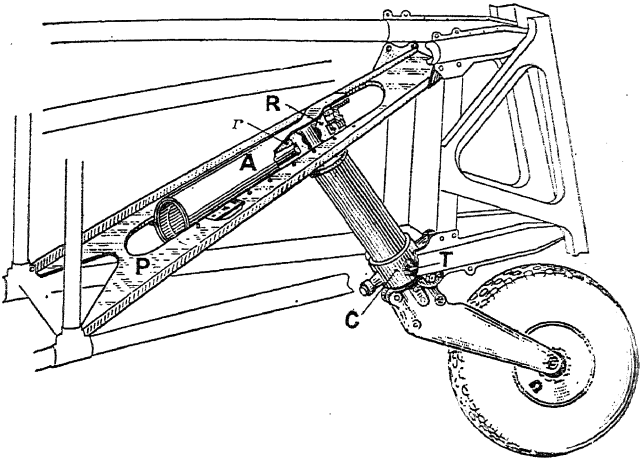

FIG. 315. MORANE-SAULNIER 330—TAIL WHEEL
(By courtesy of "L'Aéronautique")

In the Morane-Saulnier 330 (Fig. 315) the wheel fork is free to rotate in the bearings, *C* and *R*, at the bottom and top respectively. The lower bearing is a trunnion with mountings, *T*, on each side so that the fork has also rotational movement in the longitudinal direction. This is restrained at the top end, for the upper bearing, *R*, slides on the diagonal member, *P*, against the rubber absorber rings, *r*, in the tube *A*. The upper bearing, *R*, is so designed as to allow not only for the change of angle between the forkhead and the slide, but also for the slight withdrawal of the head as it moves forwards and downwards. The horizontal reaction at *T* is taken straight into the lower longerons. The vertical reaction passes up the post, where it is taken in compression by the top longerons and in tension by the diagonal member, *P*. This is neat, for *P* also carries

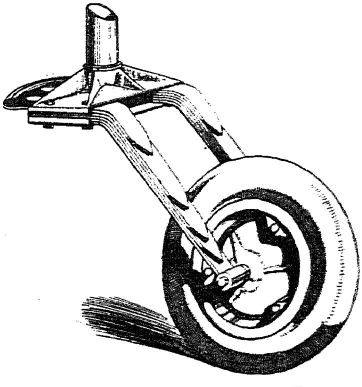

FIG. 316. COMPER MOUSE TAIL WHEEL
(By courtesy of "Flight")

compression, transmitted to it from the shock absorber *A*. The two loadings therefore tend to cancel out.

A very different system was used on the Comper *Mouse* (Fig. 316). The wheel was carried on an axle between two leaf springs, which were bent at their upper ends and clamped between two plates. The upper plate was webbed to a vertical spindle which ran in bearings on the front side of the stern post.

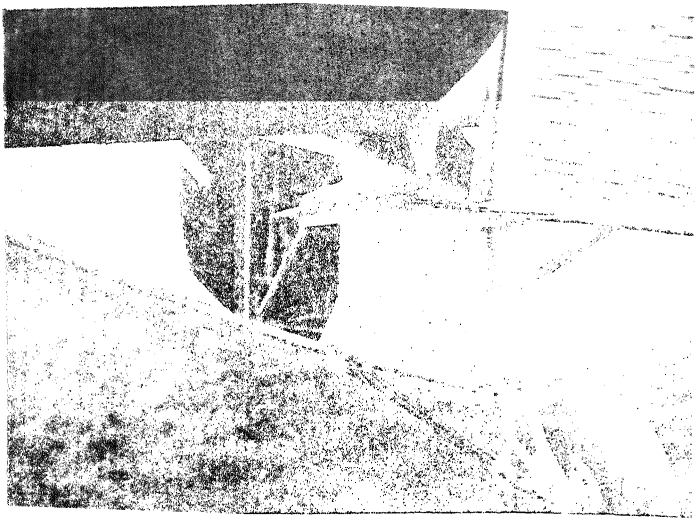

FIG. 317. BREDA 32—TAIL WHEEL
(By courtesy of Società Italiana Ernesto Breda)

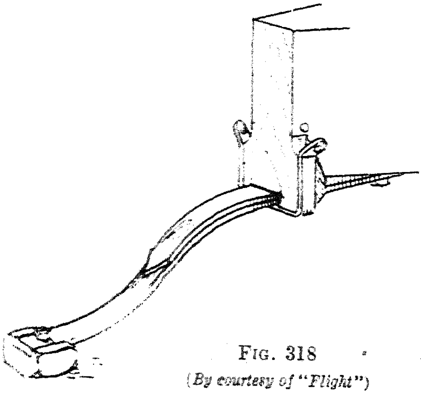

FIG. 318
(By courtesy of "Flight")

A usual form of mounting is that of the Breda 32. The wheel, which is of the low-pressure type, is carried in two forks, one to the fuselage top and the other to the bottom. These joints are hinged and the wheel is castoring. The forks are joined together at their lower end by a large welded gusset. The upper fork, which takes the compression load, is well reinforced with webs.

If not controllable, the wheel should still be free to castor in order that the tyre may not be ripped off by side load.

Wheels of the low pressure type are popular. It is claimed that they remove the need for a shock absorber in the compression member.

Although the skids and wheels in some of these examples are of the type generally known as "castoring," they are not ideally so. A perfect castor skid should always tend to centralize itself along the longitudinal centre line of the aircraft. If the hinges about which the skid rotates are mounted on a stern post which rakes aft when "tail down," then any lateral load which is big enough to overcome the friction of the hinges will throw the tail over and decentralize the skid. If the lower hinge is set off from the stern post so that the hinge centre line is vertical or raked forward relative to the ground line, the skid would be fully castoring. The constructional difficulty in doing this lies in the large bending moment which occurs in the lower hinge. Provided that the ground angle is not excessive, the trouble may be overcome by raking the whole mounting forward as in the Breda and Morane-Saulnier.

An extremely simple type of skid suitable for very light aircraft consists of a steel leaf spring firmly secured to the fuselage, with a cast-iron shoe at its lower end. In larger machines it is difficult to obtain the necessary travel economically in this way, and the leaf spring has attained little popularity. (See Fig. 318.)

The Undercarriage

The functions of an undercarriage are to dissipate the kinetic energy of vertical descent and to form with the tail skid or wheel a reasonably well-sprung carriage on which the aircraft can taxi over a rough aerodrome. Yet though it has this double purpose, it may be classed with those necessities which are unfortunate. In most aircraft the time spent in alighting, or even in taxying, is a very small percentage of their total life. Yet the undercarriage must always be there, making possibly as much as one-sixth of the weight of the structure and forming more than an eighth of the air resistance.

The problem of keeping down weight is one of the greatest which the aircraft constructor must tackle. If there is a greater, it is that of keeping down the resistance. In no part of the machine are these two more incompatible than in the undercarriage. An attempt to achieve both at the same time is made by the use of high tensile steel. But when it comes to a complete solution of the resistance trouble by withdrawing the chassis inside the structure during flight, weight may run riot, not only in the chassis itself, but in complications to the structure and in the operating mechanism.

In its most usual form, the undercarriage consists of a two-wheel chassis just forward of the centre of gravity of the machine, and a skid or small wheel at the tail. The tail skid having already been dealt with, it is only the main chassis which will be discussed here.

Fig. 319 illustrates a very common form of undercarriage which was very favoured, particularly on biplanes, for many years. It is probably the simplest and lightest which can be made and it introduces few complications into the construction of the fuselage and wing to which it is attached. At the same time the air resistance is high and its use is uneconomical in power on an aeroplane of high performance.

There are two pneumatic-tyred wheels mounted on a cross axle. The vertical load, beyond that absorbed in the tyres, is taken by two sprung telescopic members which dissipate the kinetic energy. Horizontal components of the load in the longitudinal direction are taken by the "radius," or "track" rods which run back to an anchorage on the lower longerons.

When the chassis members slope outwards towards the bottom, there is a tendency for the wheels to spread in the normal two-wheel landing. This is resisted by the axle in tension. In addition, the axle is under bending due to the overhang of the wheel beyond the point of attachment of the compression leg and radius rod. The vertical load is taken by the compression leg and the impact absorbed either by an oil dashpot, helical spring or rubber blocks inside. The leg must be jointed at both ends to allow it to swing forward in relation to the fuselage as its length is shortened telescopically and the wheel travels forwards and upwards around the arc of a circle struck from the top hinge point of the radius rod. This member is under compression in landing. As, however, the tail drops and the weight is taken, the radius rod load changes to tension, as will be understood from the geometry of the chassis. It is sometimes the practice to fit the radius rod in the opposite direction—that is, to attach it to a point on the fuselage forward of the wheel so that it slopes downwards and back. In this case its loading will be in the reverse sense of that just stated. The rod must be universally jointed at both ends, since it varies its angle to fuselage and axle in both side and front elevations as the wheel moves up and down.

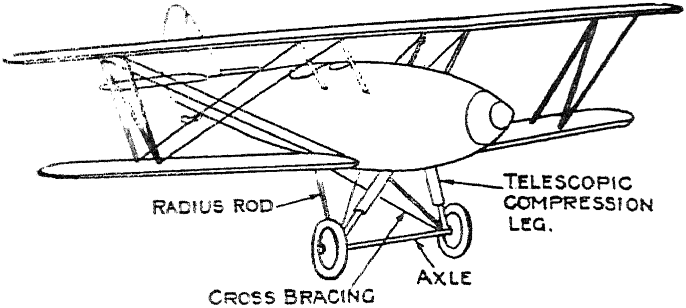

FIG. 319

The perfect two-wheel landing is rare. Owing to gusts and side-slipping, the load is more frequently taken on one wheel first. There is then a side component to be catered for. This is commonly achieved by cross-bracing the radius rods with streamline wires.

A form of trouble frequently met with in chassis of the kind just described is that the axle is damaged by fouling some obstacle when a landing is made on rough ground. In taking off from a field with long grass or scrub, speed is reduced and the take-off impeded by the low cross tube being caught up. This is a particular trouble in undeveloped countries. The split axle type of chassis was, therefore, devised. A typical example was that used on the Blackburn *Bluebird* (Fig. 320). Though possibly a little heavier than the cross axle type, there is some compensation in the absence of cross bracing wires.

It will be noticed in this case that when viewed from the front, the axle and radius rod move together as the travel is taken up in the compression leg. Their top end hinges must therefore be in line. In the previous example the fore and aft component in the fuselage at the top of the radius rod was taken by the longeron. Here the radius rods come to the centre line and a spreader tube is therefore fitted. The compression legs, which are universally jointed at their ends, are attached to the lower front spar stub fittings. The axles are subject to both bending, due to the overhang of the wheel, and end load, which varies from compression to tension according to the landing. The point of maximum bending is, of course, at the attachment of the compression leg. The stress here is inevitably big and can only be catered for by high-tensile steel. That most frequently used is an 85-ton nickel chrome steel to B.S. Specification T.2. Weight may be saved by tapering the bore. This process, together with the bending and drilling, is best done by the tube manufacturers. An example which may be cited is that of the axle of a well-known light aeroplane, which is $1\frac{3}{4}$ in. outside diameter throughout. From the outer end as far as the inner side of the bend the thickness is 10 s.w.g. The next 18 in. is a tapered portion where the thickness drops to 18 s.w.g., at which it remains up to the top. A section of almost constant strength is thus obtained, and the saving in material and weight is considerable. In fact, the saving in material cost may be made to balance the expense of the extra operation.

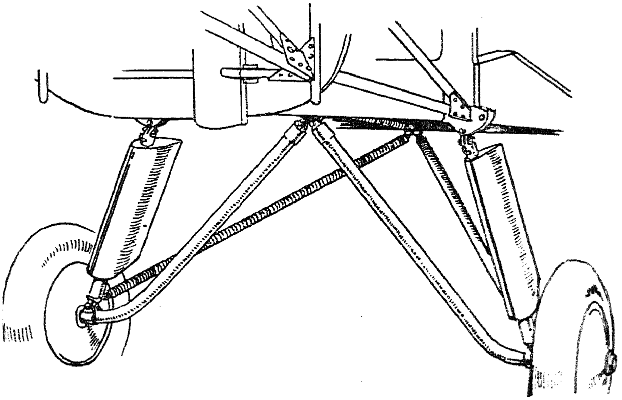

FIG. 320. BLACKBURN "BLUEBIRD" UNDERCARRIAGE
(*By courtesy of "The Aeroplane"*)

A simple form of split axle undercarriage for a large, low-wing monoplane, the Breda 32, is shown in Fig. 321. The wheel, which is braked, is carried in two forks. The rear fork is attached to the bottom of the rear truss of the spar. The front fork, at its top end, is connected to the lower end of an oleo-pneumatic shock absorber, already shown in Fig. 170A. The absorber, which on many machines is objectionable on account of its large diameter and consequent large air drag is, in this machine, completely enclosed in the leading edge of the wing behind the outboard engine mounting. This allows it to be attached to the top boom of the front truss, thereby improving the angle at which it works.

To take the side load when turning on the ground or in an unsymmetrical landing, a radius rod runs from the wing root to the wheel hub, where it is attached in ball-and-socket joint. If this type of wheel mounting is used, care must be taken in the design to allow for the quick removal of the complete wheel so that it may be replaced easily in case of puncture. The light tubular framework which carries the wheel fairing can be seen in Fig. 321. Though this chassis is not retractable, every effort has been made to reduce drag, without, as far as one can see, paying for the refinement with increased structure weight.

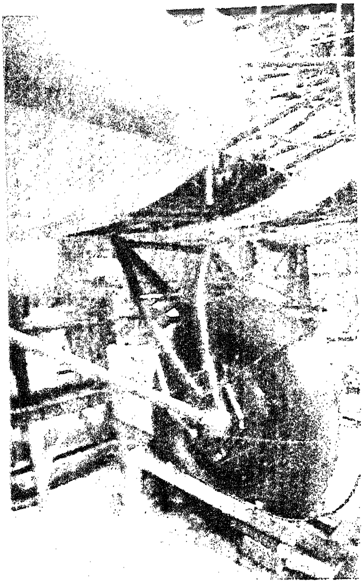

Fig. 321. Breda 32—Undercarriage

y of *Società Italiana Ernesto Breda*)

The success of an undercarriage, no less than that of any other component of an aeroplane, depends very much on its detail design. The design of the axle has already been discussed in considering the loads imposed on the chassis. The track rod calls for little comment. Though it may be strut and tie in turn, it is to be expected that the compression load will be the deciding one in fixing its size, and that it will be an "Euler" strut (i.e. that its length will be big in relation to its radius of gyration). Hence mild steel to Specification T35 or T45 will probably be the most economical material to use. The notes on interplane struts (Chapter III) are in many ways applicable. A streamline section is frequently used, a blunt one having every advantage since it has a relatively higher radius of gyration. The air flow, being diagonally across it, will increase its effective fineness ratio. On large machines a circular member with added fairing may be cheaper and lighter, but it is unlikely to be as advantageous as in the case of the interplane strut. This point will repay investigation in every case.

The question of track width, or distance between the wheels, is an important one which must be decided in an early stage of design, since the loads involved are likely to affect many of the main fuselage and wing structural members. From many points of view a wide track is desirable. It gives the machine a wide base and consequently good stability in a sideslip landing or against the effect of a cross wind when taxying. In landing it tends to give a bigger angle of yaw when any hummocks or unevenness are hit, and consequently to pull the machine up in a shorter distance. This same quality, however, will delay the take-off. But with wheel brakes these considerations need not arise, and the track may be decided by the requirements of stability and the radius of turning with one wheel locked. Looking at it now from the point of view of the compression leg, it will be seen that for equal travel in that member the narrow track will feel softer in running on uneven ground, but the lateral rocking will be greater than with the wide one.

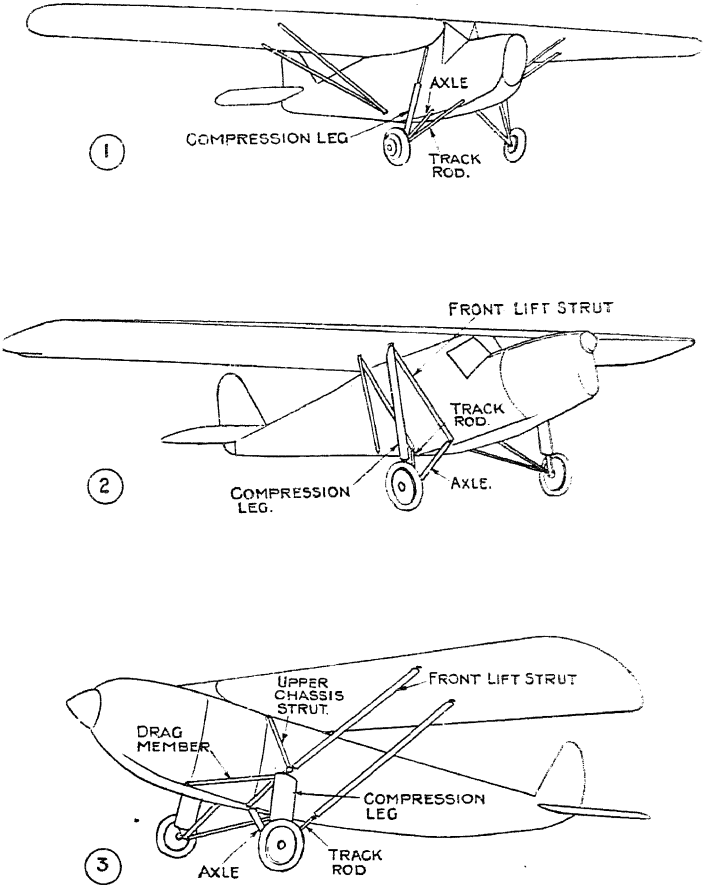
AXLE
COMPRESSION LEG
TRACK ROD.
①
FRONT LIFT STRUT
TRACK ROD.
COMPRESSION LEG.
AXLE.
②
UPPER CHASSIS STRUT.
FRONT LIFT STRUT
DRAG MEMBER
COMPRESSION LEG
AXLE
TRACK ROD
③

Fig. 322. Types of Chassis for High-wing Monoplanes

A track of one-fifth to one-quarter of the wing span appears to be general in most designs.

In a high wing monoplane there may be some complication of the chassis by the addition of lift struts. Fig. 322 gives some typical cases. The first is a very popular arrangement for machines in the light aeroplane class, with folding wings hinged about the rear spar joint. There are no complications, the two structures being independent. The compression leg slopes inwards and is therefore more heavily loaded than if vertical. A strong cross strut must be provided in the fuselage to take the horizontal component of this load at the top end. The type is not particularly suitable for medium- and large-sized aircraft as, owing to its long length, the compression leg becomes unwieldy and heavy.

In the second type, the compression leg load is met at the top by the front lift strut, which takes it back to the fuselage and at the same time balances a compression across the centre section of the front spar.

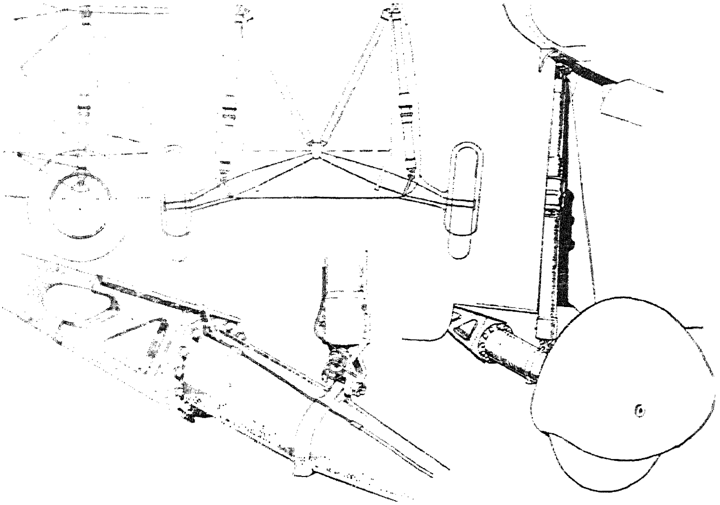

FIG. 323. ARMSTRONG-WHITWORTH "ATALANTA" UNDERCARRIAGE
(*By courtesy of "The Aeroplane"*)

It is a simple arrangement, and economical in material since it reduces the number of members, making two perform a dual role. The objections to the system are that it is not applicable to folding wings, and that in dismantling the wing the undercarriage must come off too, a point which will be appreciated in maintenance or repair.

The third type, though not aerodynamically "clean," has been much used in the past. It has appeared, with small variations, in the designs of such well-known firms as de Havilland, Fokker, Curtiss, Farman, Dewoitine, Ryan, and Stinson.

The compression leg is vertical and short, and therefore without the objections to the first type in this figure. Its upper end is mounted at the apex of a triangular pyramid, consisting of the lower half of the front lift strut, the upper chassis strut and the drag member. The landing load is taken by the first two of these, by tension in the one and compression in the other, the drag member catering only for the longitudinal component when the leg is out of vertical. The upper chassis strut is attached to a fuselage cross member, not to the main plane spar. The machine, therefore, remains perfectly supported when the main plane is dismantled. Two of these members, the lower half of the lift strut and the drag member, carry loads when the aircraft is flying, and thus serve a double purpose. If it were possible to use already existing structural parts for all the chassis loads, much objection to the parasite drag of an undercarriage would be removed. The double axle and the track rod of this chassis are normal and of the kind already described. Though outside the scope of this chapter, it is interesting to notice here that folding may easily be achieved with a wing structure of this kind. The top half of the front lift strut is released at its lower end and hinged back to clip into a fitting on the rear lift strut. It then acts as a "jury" member, supporting the front spar as the wing hinges back about the rear spar. With a little ingenuity it is possible to devise a mechanism which automatically withdraws the front spar bolt when the front lift strut is released.

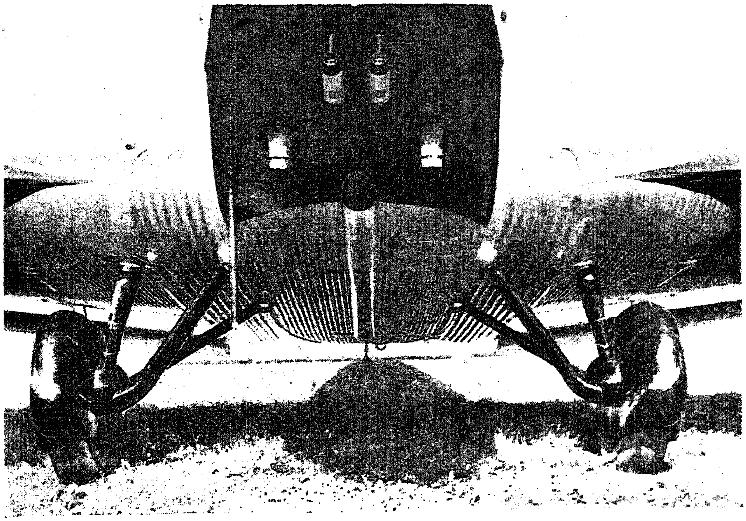

FIG. 324. JUNKERS 52—UNDERCARRIAGE

(By courtesy of Junkers-Werke)

An original method of reducing undercarriage drag on a high-wing monoplane has been made in the Armstrong-Whitworth *Atalanta*. The difficulties of designing a retractable chassis for this type of machine are great, but in the *Atalanta* only the wheels and the outer ends of the axles are exposed. This arrangement has been secured at the expense of track, which is very narrow for the 90 ft. span of this machine.

The axles are double-tapered tubes hinged on the fuselage centre line. The largest diameter of the axle is at its mid length, where, of course, the bending moment is greatest. The compression legs run up to the top longerons, from which points struts slope down to meet the centre axle attachment. This machine has no radius rods, but a triangular tie plate from each axle runs forward to a fixing on the bottom longeron. In principle this chassis is similar to the first type illustrated on p. 275, and its aerodynamic cleanness is due to the wide space between the fuselage structure and the fairing.

The axles are forgings bent, machined, and heat treated.

Such variety of method is not possible in the low wing monoplane. The track must be wide to prevent wing tip damage, but the undercarriage weight may be less owing to the shorter length of compression

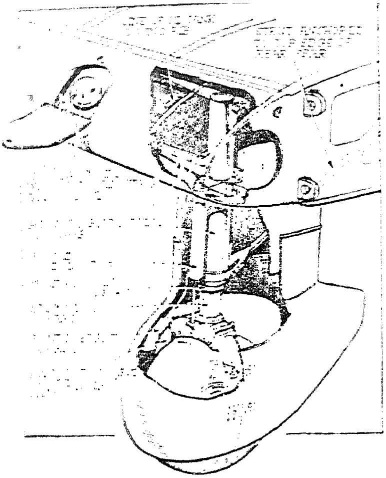

FIG. 325. "VEGA GULL" UNDERCARRIAGE

(*By courtesy of "The Aeroplane"*)

leg possible. When the wing section is thick the vertical load from the leg can be taken in bending in the front spar.

The undercarriage of the Junkers Ju 52 is an example of this. The undercarriage legs run up into the wing at the front spar (see Fig. 324) whilst the axles and radius rods are attached to the fuselage at the wing root.

More modern machines of this kind are usually fitted with retractable undercarriages. These are dealt with later. On smaller low wing monoplanes, however, the fixed undercarriage is still popular since wheel dimensions would impose too thick a wing section. An effort is made therefore to reduce aerodynamic drag and a good example from the Percival *Vega Gull* is shown in Fig. 325. The compression leg is made sufficiently stiff to carry the whole side load in bending. Fore-and-aft load is also taken in bending through the lower half of the compression leg and then through the back stay to the rear spar.

The mounting of the leg on the front spar is made very rigid and the spar from this point to the fuselage must be stiff. With a normal track, however, a cantilever spar which is stiff enough to take the air load without undue deflection will carry the undercarriage load with only local reinforcement at the mounting. It must be realized that there is torsion on the spar due to the forward offset of the leg and also a component along the rib from the upper end fitting of the back stay.

The wheel is mounted centrally in a stout bridge piece at the lower end of the compession leg. The lower telescopic portion is splined to prevent rotation under side load which would occur when the point of tyre contact with the ground does not lie on the vertical centre line of the leg. It is, of course, behind this centre line when the tail is down.

In the T.K.2, a low wing monoplane produced by the de Havilland Aeronautical Technical School, this type of undercarriage was taken a stage further by making it a full cantilever, the back stay being dropped (see Fig. 326). In a tail down landing with brakes on, the most severe case which can be imposed (since the pilot would not land tail *up* with brakes on) is the horizontal backward component which is assumed by the Air Ministry to be one quarter of the vertical load. If when the tail is down the compression leg slopes back at an angle of one in four, the forward component of the vertical load is balanced out against the backward brake load. The back stay is not then necessary and the mounting can be made sufficiently stiff to take all the other loads. The wing structure must, however, be made stiff in torsion as well as in bending.

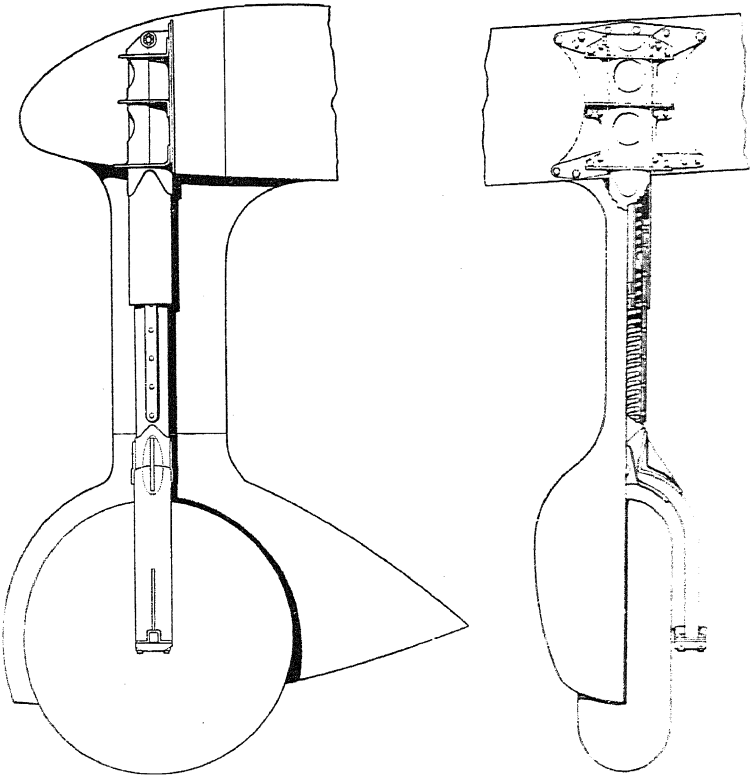

FIG. 326. T.K.2 CANTILEVER UNDERCARRIAGE

In spite of its advanced aerodynamic and structural design this undercarriage is extremely simple to maintain. The ends of the axle are squared and fit into square recesses in each arm of the fork. To drop out a wheel it is only necessary to remove the caps over these recesses. The whole chassis may be removed by taking out the single bolt at the top end of the spar sleeve. This bolt is in shear from the vertical load and also the side load torsion case mentioned above. The backward compound goes in bearing in the spar sleeve.

The lower telescopic half of the leg was not splined but had a key

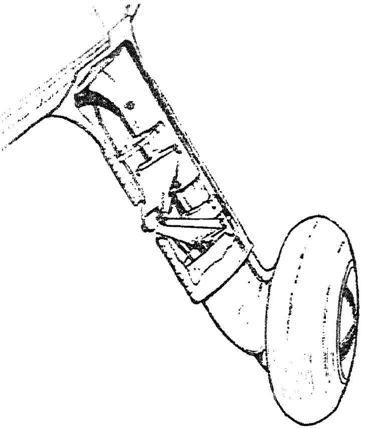

FIG. 327. CESSNA C-34 UNDERCARRIAGE

(By courtesy of "Flight")

riveted on each side. The whole surface of the lower half was double plated with chromium to reduce friction and the possibility of seizing. It ran in a phosphor bronze bearing in the upper half, this being slotted to take the keys. The rivets holding the keys and bearings were countersunk flush on their wearing surfaces.

In an American high wing monoplane, the Cessna C-34, the undercarriage legs are cantilevered out diagonally from the fuselage (see Fig. 327). This is probably the best compromise which can be made in a single engined high wing monoplane and it is much cleaner than the examples shown in Fig. 322. For the same vertical travel the travel up the line of the leg is much greater and the bending loads are severe. Torsion is taken not by splining but by two triangular brackets hinged respectively to the upper and lower telescopic portions.

In the Letov S-231 fighter, the main undercarriage members run up similarly into the fuselage sides, but at a higher level. They then bend down sharply to meet at hinges on the centre line. The travel is damped out in oil dashpots tied back to the lower longerons. This chassis is braced with wires running down from the centre hinge line so that there is no change in the wire length as the wheel travels upwards. (Fig. 328.)

Another solution of the single member chassis appears in the Gloster Gladiator (Fig. 330). A single bent tube is mounted rigidly to the fuselage on each side pointing diagonally downwards and outwards.

This is made of high tensile steel and must be stiff enough to take all the undercarriage loads in combined compression and bending. It must also take the brake load in torsion. The shock absorber in this case is mounted inside the wheel hub. (See Figs. 331 and 332.)

The advantages of this design are its aerodynamic cleanliness and the simplicity of maintenance. Its disadvantages lie in the restricted travel due to the fitting of the shock absorber inside the hub and in the multiplication of stresses in the bent axle member.

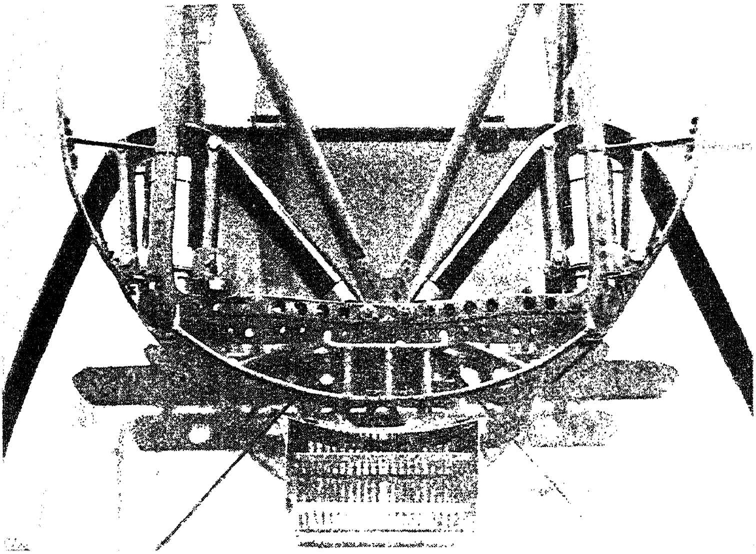

FIG. 328. LETOV S–231 FIGHTER: UNDERCARRIAGE ATTACHMENT TO FUSELAGE, SHOWING SHOCK ABSORBERS

(*By courtesy of Letov*)

A recent Dowty development is shown in Fig. 329. In some ways this is similar to the internally sprung wheel mentioned above. The shock-absorber unit itself is small and located close down to the wheel. By a simple system of leverages a small travel in the shock-absorber unit itself is magnified many times. The whole unit is extremely simple and can be mounted on a cantilever strut, thus making a very clean undercarriage if suitably faired in. It is also very simple to retract since only one member is involved.

Retractable Undercarriages.[1] The popularity of the cantilever monoplane in recent years has favoured the development of retractable undercarriages. The wing section is sufficiently thick to provide a housing for the wheel when withdrawn and to contain the necessary mechanism. In multi-engined machines the rear portion of the cowling behind the engine is usually used to contain the retracted wheel, whilst on amphibian flying boats the undercarriage may be withdrawn into the hull sides. Each of these types will be dealt with.

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[1] Many of the examples in this section are taken from the *Journ. R.Ae.S.*, April 1936, "Retractable Undercarriages," G. H. Dowty, to which the reader is referred for a fuller treatment.

In a single engine machine where the wheel must go up into the wing, the direction of retraction is usually sideways since the wing is not sufficiently deep to take the diameter of the wheel. An example of this is seen in the Heinkel He.70 (Fig. 333). The wheel is carried on an overhung axle stub and folds up outwards into a large cavity in the under surface. Since there is no longitudinal movement of the wheel,

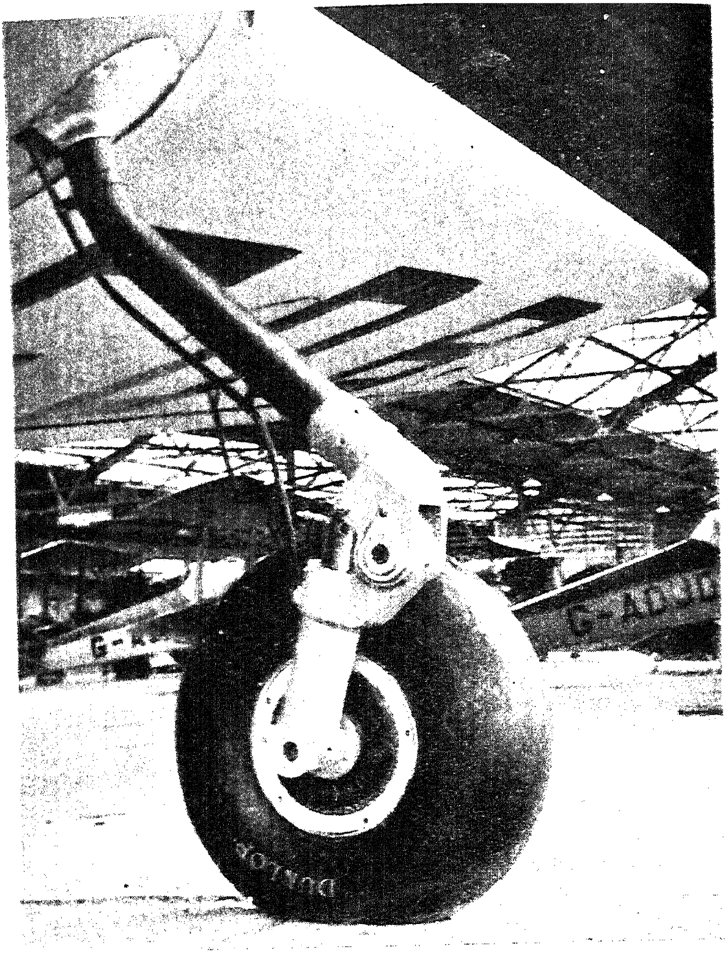


Fig. 329. Dowty Shock Absorber

(*By courtesy of G. H. Dowty, Esq.*)

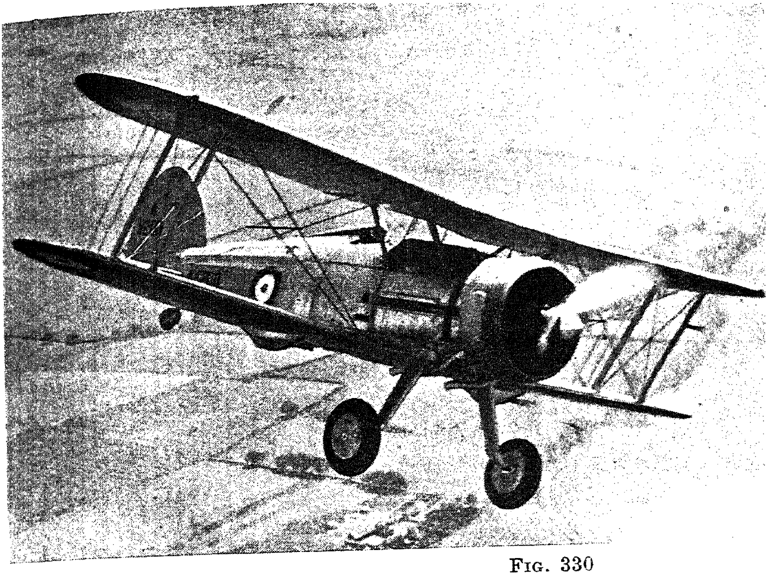
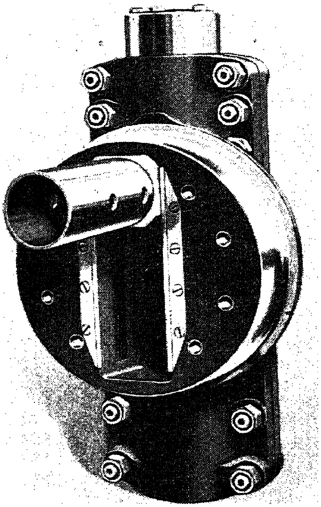


Fig. 330

(By courtesy of G. H. Dowty, Esq.)



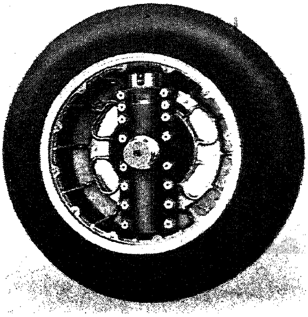


Fig. 331

Fig. 332

Gloster "Gladiator" with Internally Sprung Wheel

(By courtesy of G. H. Dowty, Esq.)

there is similarly no change in the position of the centre of gravity which will affect the trim. The air resistance and its line of action will, of course, be different in the two conditions of wheels up and wheels down.

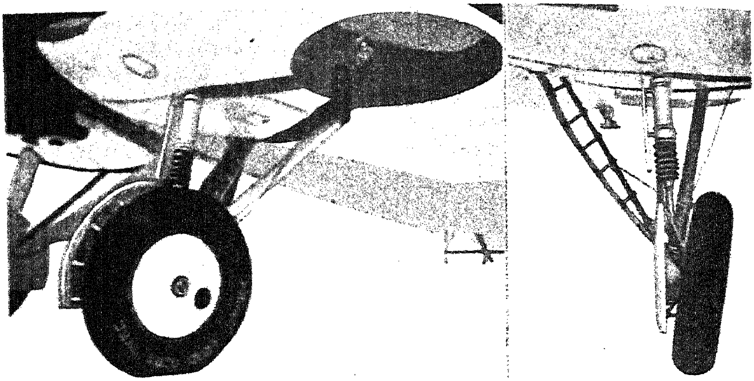


FIG. 333. RETRACTABLE UNDERCARRIAGE, HEINKEL HE. 70

(By courtesy of "The Aeroplane")

The wheels of the Vultee transport monoplane fold inwards, not outwards like those of the Heinkel. The mechanism is shown diagrammatically in Fig. 334. The wheel is carried on an offset axle at the lower end of the compression leg. This is hinged at its upper end and has a sector of a gear which works in a worm driven by an electric motor. The movement is thus irreversible and, given sufficient local

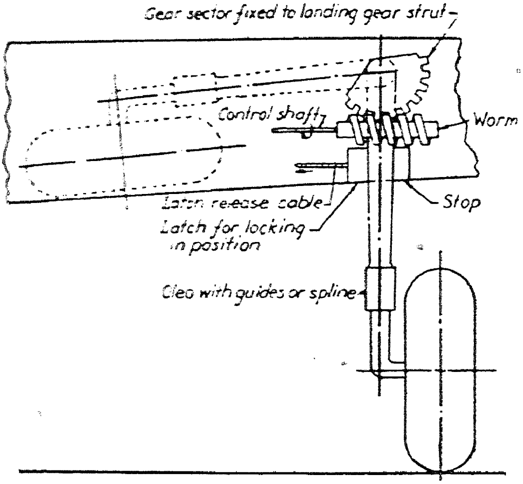

Gear sector fixed to landing gear strut
Control shaft
Worm
Stop
Latch release cable
Latch for locking in position
Oleo with guides or spline

FIG. 334. VULTEE RETRACTION GEAR

(By courtesy of G. H. Dowty, Esq., and The Royal Aeronautical Society)

strength in the detail parts of the gear and worm, the aeroplane may be landed with the wheels in any intermediate position. An emergency manual control is also provided together with signal and warning devices. The time taken to raise or lower the wheel by means of the electric motor is 15 seconds. Speedy raising is desirable since the drop in resistance improves the rate of climb, and should the engine fail just after taking off a shorter landing may be made on the underside of the machine, though, of course, with some damage to the structure.

In the Vultee "V—1A" the main spar is 35 per cent of the chord from the leading edge, which gives sufficient room for housing the wheels

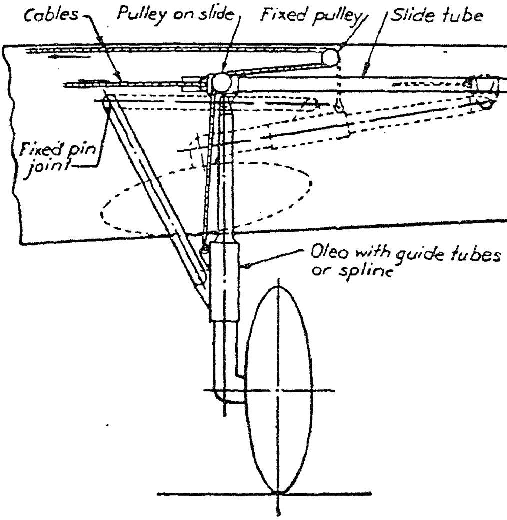


FIG. 335. U.S. AIR CORPS (ENGINEERING DIVISION) RETRACTION GEAR

(By courtesy of G. H. Dowty, Esq., and The Royal Aeronautical Society)

in front of the spar, leaving the still deep section behind for the fuel tanks. As on the Heinkel, the compression leg and wheel have attached to them, edge on to the line of flight, the fairings which cover the wing recesses when the wheels are up. An important point in connection with these fairings is that when up, they carry their share of the air pressure on the undersurface of the wing. They must, therefore, be reasonably rigid. Further, this upward pressure will counteract the weight of the chassis at the moment when lowering begins. In the manually operated chassis of a certain small cantilever monoplane, it was found extremely difficult to start the downward movement against this pressure.

A manually operated mechanism for sideways retraction, designed by the Engineering Division of the U.S. Air Corps, is shown in Fig. 335. Tension on the upper cable first pulls the slide to the right. When this comes under the upper pulley the cable leaves the slide pulley and lifts the wheel directly. The travel of the wheel is governed by the slide and by the hinged side member.

Whilst the development of retractable undercarriages has been

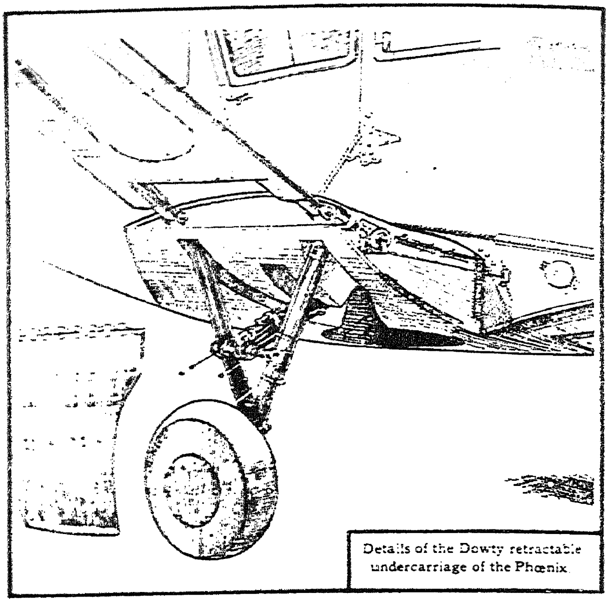

Details of the Dowty retractable undercarriage of the Phœnix.

FIG. 336. HESTON "PHOENIX" UNDERCARRIAGE

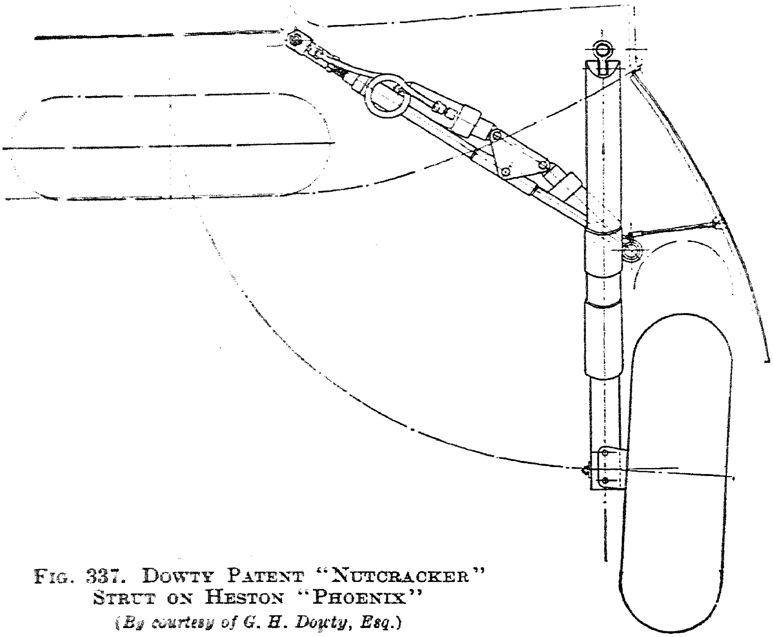


FIG. 337. DOWTY PATENT "NUTCRACKER" STRUT ON HESTON "PHOENIX"

(By courtesy of G. H. Dowty, Esq.)

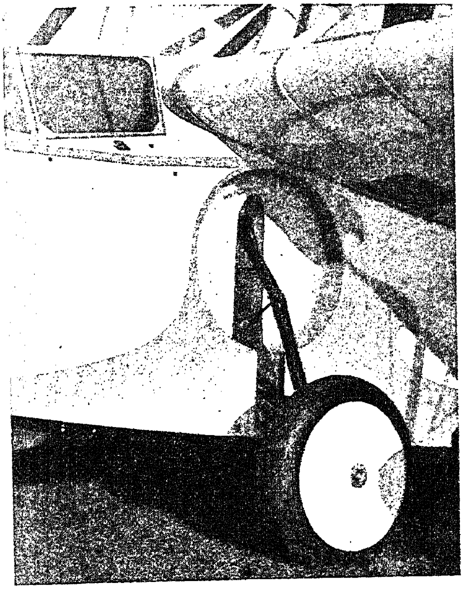


FIG. 338. DORNIER "LIBELLE" AMPHIBIAN—WHEEL DOWN
(By courtesy of Dornier Metallbauten G.m.b.H.)

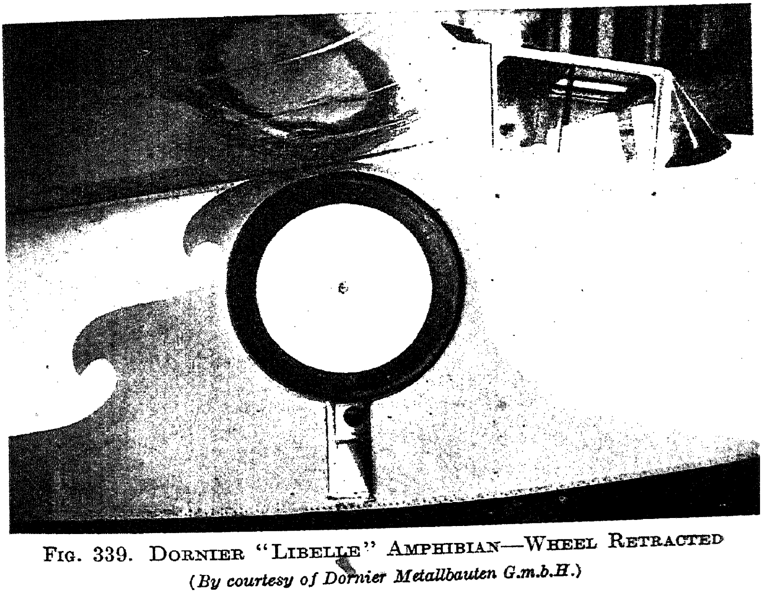
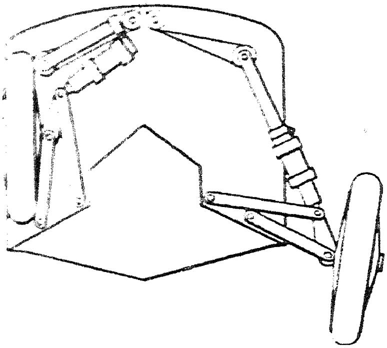


FIG. 339. DORNIER "LIBELLE" AMPHIBIAN—WHEEL RETRACTED
(By courtesy of Dornier Metallbauten G.m.b.H.)

rgely coincident with and dependent upon the development of the w wing cantilever monoplane. some neat mechanisms have been evised for biplanes and sesquiplanes. One of these, fitted to the leston *Phoenix*, is illustrated in Fig. 336.

This retracts the wheel sideways and inwards. Two opposed hydraue jacks operate on an offset link at the middle of the side bracing tube hich is divided by a knuckle joint. The jacks work simultaneously and ush the knuckle joint upwards. The consequent shortening of the ube pulls the compression leg and wheel inwards.

In the Dornier *Libelle* Amphibian (Figs. 338 and 339) the wheel moves vertically and inwards to a recess in the hull side. The upper mb of the triangulated structure has a knuckle joint at its mid



GRUMMAN "JF-1" AMPHIBIAN UNDERCARRIAGE

(By H. [illegible], Esq., and The Royal Aeronautical Society)

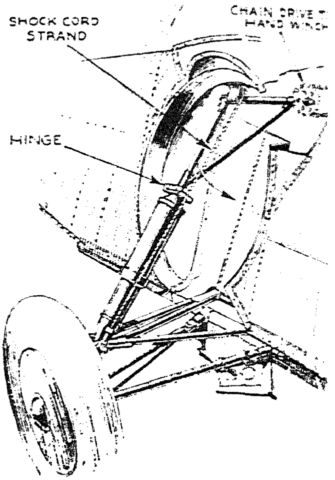


FIG. 341

(By courtesy of "Flight")

length. As the wheel is lowered this passes over dead centre and landing loads consequently put tension in the cable attached to the knuckle. To retract, the knuckle joint is pulled inboard. Watertight bulkheads are, of course, necessary on each side of the recess into which the chassis is drawn. The longitudinal strength of the hull must be secured by continuous members above and below.

A similar arrangement is used on the Grumman JF-1 Amphibian of the U.S. Navy. This is operated by a hand winch through a system of chains and sprockets. The weight of the chassis is counterbalanced by means of shock absorber cord and about 45 turns of the handwheel are needed to raise or lower it. (Figs. 340 and 341.)

The first example of backwards retraction in England was found in the Airspeed *Courier* (see Fig. 342). The back stay, which runs from the bottom of the compression leg to the rear spar, has a knuckle joint at one-third of its length from the bottom. An hydraulic jack by which the chassis is raised runs from this knuckle to the top of the rear spar.

The jack consists of a double-ended pump, and the piston is moved by pumping oil in on one side and withdrawing it on the other. The shortening of the jack breaks the knuckle joint and lifts the compression leg and wheel about the hinge on the lower flange of the front spar. The operation is controlled from the cockpit by means of a hand pump and three-way cock as shown in the diagram.

The wheels of the Douglas D.C.2 retract upwards and forwards about hinges at the top ends of the back stays, as shown in Fig. 343. This back stay is attached to a stirrup round the wheel and there are two compression legs to each wheel. These are joined above the wheel by cantilever triangles of tube meeting at a centre pin. Above this is a pyramid, to the forward pointing apex of which is fastened the hydraulic jack.

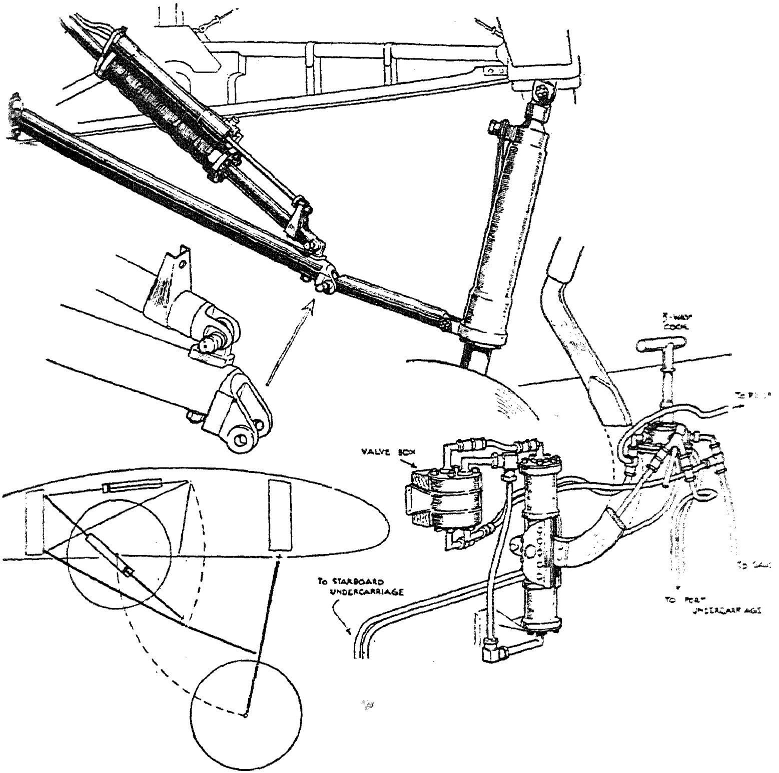


FIG. 342. RETRACTABLE UNDERCARRIAGE, AIRSPEED "COURIER"
(*By courtesy of "The Aeroplane"*)

A method of retracting forwards recommended by Dowty[1] is illustrated diagrammatically in Fig. 344. He says of this that it "does not depend upon broken limbs of any kind; in fact, this system is the very essence of mechanical simplicity. The undercarriage structure conforms to normal practice with the usual side "V" comprised of front shock strut and rear brace pinned to front and rear spars respectively. The upper part of the shock strut, however, is housed in another cylinder pivoted to the rear face of the front spar. This cylinder acts as a jack, the upper part of the shock strut forming the piston, or ram. Retraction is carried out by pumping oil below the piston, thus shortening the shock strut and lifting the wheel. A worth-while feature is the balancing effect obtained by the shortness of the C.G. arm from the pivot during the raising operation."

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[1] See *Journal R.Ae.S.* April, 1936.

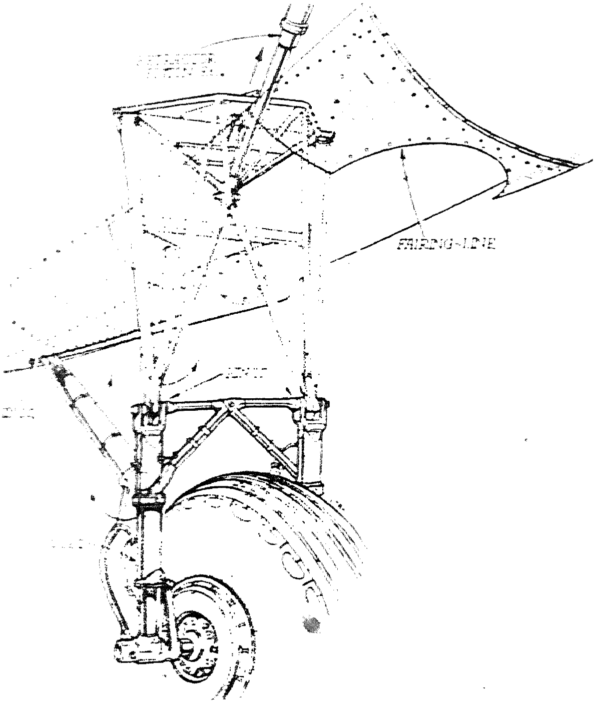

FIG. 343. DOUGLAS D.C.2 UNDERCARRIAGE
(*By courtesy of "The Aeroplane"*)

The subject of operating mechanisms is a big one, with which it is not proposed to deal in detail since proprietary articles (pumps, motors, control values, etc.) are usually used to build up the system.

Existing methods may be classified as follows—

1. Manual Mechanical.
2. Manual Hydraulic.
3. Electro-Mechanical.
4. Electro-Hydraulic.
5. Engine-driven Hydraulic.
6. Pneumatic-Hydraulic.

The Manual Mechanical system is confined to small machines where the weight to be lifted and its travel are small. Further, the leads of cables, etc., from the cockpit to the undercarriage must be simple, or the weight and frictional losses will be too great. (See Fig. 345.)

In larger machines up to 4,000 to 5,000 lb. all-up weight it is simpler to use an hydraulic lead from the cockpit with a system such as that shown in Fig. 342. A few points should be remembered. It is difficult to provide a light flexible coupling to stand up to the pressures used. Therefore the jack should operate as far as possible in one straight line. If its lengthening and shortening involve rotation about one end this problem of a flexible coupling will arise. A further source of difficulty is the frictional loss in the pipe lines, and therefore as large a diameter as possible should be used with the maximum radii at the bends.

In military aircraft and in large commercial machines, manual operation is not practical and the designer must turn to electrical or engine driven operation. The former is heavy and liable to unforeseen breakdown. There should always be an emergency lowering gear operated by hand. The engine-driven hydraulic pump is inefficient and must operate all the time that the engine is running, by-passing the oil except when in use.

With regard to the pneumatic hydraulic system, Dowty suggests that this would prove to be light. Air alone would not be sufficient without storage bottles of prohibitive weight. By means of a pneumatically driven oil pump, however, the pressure can be geared up by as much as ten.

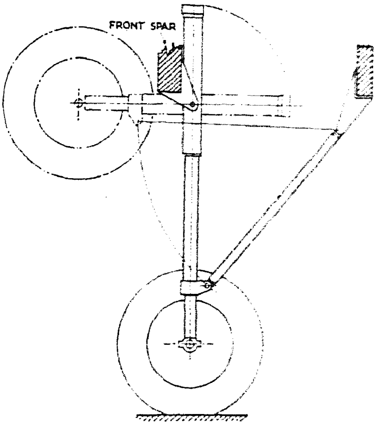

FIG. 344

(By courtesy of G. H. Dowty, Esq.)

For military aircraft the Air Ministry require locking devices and a duplicate system of indicators and warnings to meet every emergency. Whilst the use of a retractable undercarriage in itself will give an improved performance, an elaborate emergency system may seriously reduce the military effectiveness of both pilot and machine. For civil aircraft where the official requirements are as yet optional, the weight and elaboration of the undercarriage retraction gear with its accessories should be compared with those of the other controls. A forced landing due to failure of the elevator controls, for example, would be extremely hazardous, but a landing with the chassis jammed in the "up" position may be and has been brought off with little damage to the machine. If a sense of proportion is lost the retractable undercarriage will be severely handicapped.

Attention paid to the following points will prevent some of the troubles which might cause unsatisfactory working.

1. The travel of the compression leg must be known exactly so that the recesses for the wheel and members of the chassis will always fit.

This is particularly important for sideways retraction of the types shown in Figs. 333, 336 and 338.

2. The working parts must be protected from mud, rainwater, spray, etc., which would set up abrasion and corrosion. They must be accessible for inspection, lubrication and maintenance.

3. The mechanism must be strong enough to take the forces due to operations in flight.

4. It must not be possible to damage the mechanism by overwinding but in electrical or hydraulic systems where one side may operate more quickly than the other, the pilot must be able to work the system until both sides are fully down.

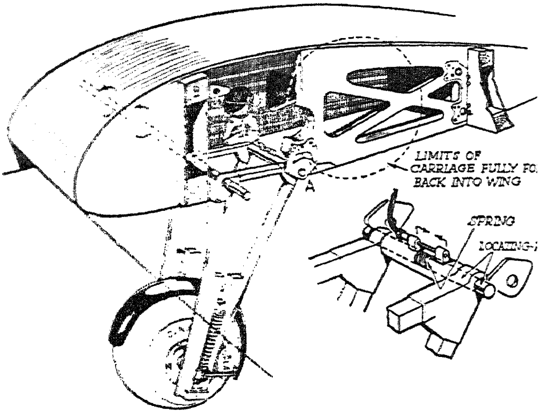

FIG. 345. RETRACTABLE UNDERCARRIAGE, COMPER "MOUSE"
(*By courtesy of "The Aeroplane"*)

5. The whole structure must be a sound mechanical job in which every possible cause of failure has been foreseen.

The Compression Leg. It is not proposed to go into the design of the shock absorber, except in general terms, since this is more a mechanical than a structural feature.[1] There are several alternative methods available. Rubber in tension was at one time used largely as the absorbing medium. It was applied either as a number of rings of rubber or as a length of rubber cord wound continuously. This type has largely been superseded now owing to the unreliability of the cord and because it does not dissipate the kinetic energy satisfactorily. Later types of compression leg incorporate some kind of recoil absorber to prevent the aircraft bouncing unduly. The ideal leg allows the machine to travel across the ground steadily, all unevenness being taken up in the shock absorber. The effect of this, not only on the personal comfort of the occupants, but also on the take-off qualities of the aeroplane, will quickly be appreciated.

Rubber in compression has many advantages over the same material in tension. It is easier to fit, suffers less from deterioration, and has better absorbing qualities. A simple method of applying it is to make the top or fixed portion of the leg in the form of a chamber open at its lower end. Into this are put circular rubber rings of a square cross section, separated by thin aluminium plates. A piston attached to the top of the lower portion of the leg transfers the load from the wheel. When this load is relieved the rebound is taken in a rubber ring between the underside of the piston and the closing cap of the compression chamber, which also acts as a guide for the lower tube. The arrangement is shown diagrammatically in Fig. 346. An approximately square cross section of ring has been found to give the best results. The external diameter of the rubber should be sufficiently less than the internal diameter of the chamber to allow free expansion sideways under load. The separator plates, which should be a sliding fit in the chamber, must be smooth surfaced to encourage the rubber to spread. The rings are located on the plates either by being moulded on to them or by lipping the centre hole in the plates.[1]

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[1] See "Shock Absorbers for Aircraft Landing Gear," by W. S. Hollyhock, in *Flight* (Aircraft Engineer Supplement), 24th April, 1931, also "Undercarriage Developments," by Dowty, *Journ. R.Ae.S.*, February, 1930.

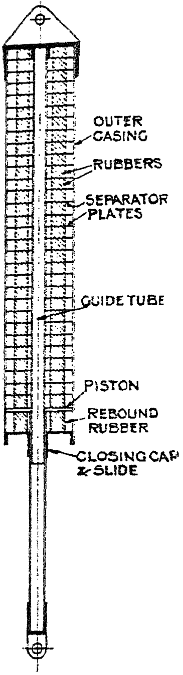

FIG. 346

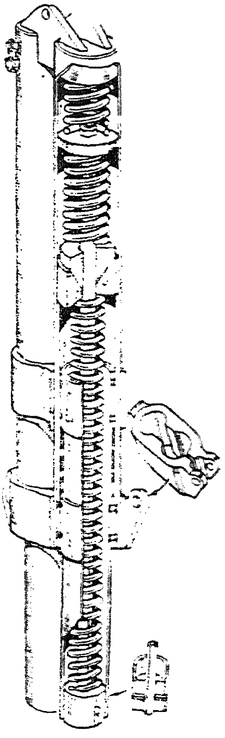

FIG. 347

The leg is usually charged with a slight initial compression applied through the rebound rubber by the closing cap. This may be made equal to 0·5 to 0·75 of the static load on the leg.

A rubber compression leg will be cheap, simple and light for a small aeroplane, and gives quite satisfactory results. In medium and large-sized machines the external diameter of the compression chamber necessary to accommodate the rubbers becomes excessive.

An alternative arrangement is to provide a strong telescopic centre guide with external rubbers, which may be of a streamline plan form. The whole is enclosed in a light aluminium fairing attached to the top fixed portion, or telescopic and attached to both fixed and sliding tubes.

Helical steel springs are sometimes used in much the same way as compression rubbers. The weight, however, becomes big if anything but a small load is to be taken. Though heavier than rubber, springs may be of advantage when long service is expected and spares difficult to procure. They are particularly suitable for warm climates.

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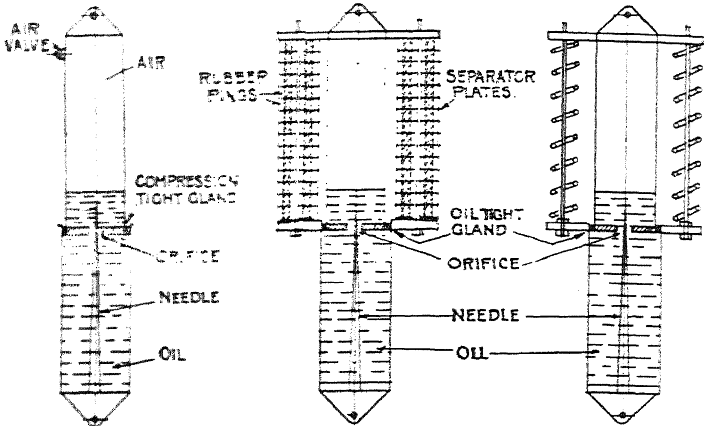
[1] See "Compression Rubbers," by G. H. Dowty, A.F.R.Ae.S., in *Flight* (Aircraft Engineer Supplement), 24th June, 1926, for design data and further particulars.

A difference to be noted between rubber and springs is in their absorption properties. Springs have an almost even resistance to an evenly applied load until they become solid; that is to say, their absorption curve is a straight line. Rubber, on the other hand, has a gradually increasing resistance to an evenly applied load. The travel is at first big and reduces as the rubber hardens. It therefore gives a softer but more bouncing chassis for taxying. An example of a steel spring leg from the de Havilland 86 type is given in Fig. 347. This compression strut, designed by Dowty, has three springs. Between the lowest and second are split cones which expand under load and bear hard on the tube walls. Some of the kinetic energy is thus converted by friction into heat which is dissipated.



OLEO-PNEUMATIC OLEO-RUBBER. OLEO-SPRING.

FIG. 348

The type of compression leg used almost universally on large and medium-sized aircraft embodies the principle of the oil dashpot. In this the application of the load forces oil from a container in the lower moving portion of the leg through a small orifice into the top portion. The resistance, of course, depends on the size of the orifice, oil, like all liquids, being incompressible. The energy of impact is not stored up, but used in transferring the oil from one chamber to the other. The leg would therefore go solid without rebound if some external means of restoring it were not added. The dashpot is combined with a system of returning the oil to the lower chamber immediately the load is relieved. Several methods are available. Fig. 348 illustrates three of these diagrammatically—the oleo-pneumatic, the oleo-rubber, and the oleo-spring. The air in the oleo-pneumatic leg is under an initial compression. As the oil is forced through the orifice the pressure increases. At any momentary reduction in the load the pressure is reduced by forcing the oil back. The initial compression of the air is such that it exactly balances the weight of the machine when standing with the legs in the static position.

A needle is shown attached to the moving portion of the leg and protruding up through the orifice. It is tapered and thereby reduces the effective size of the hole as the travel approaches its maximum. At the same time it gives easy taxying qualities.

The properties of such a leg may be greatly modified by varying the orifice and needle diameters, the size of the air chamber, and with it the initial compression.

The principles of the oleo-rubber and oleo-spring legs are the same as that of the pneumatic. Rubber rings or springs, as already described, are used. Though heavier than the compressed air leg, there is a slight gain in that the upper chamber, being at atmospheric pressure, does not need to be of so robust a construction. Other objections to the pneumatic system are the difficulty and cost of making and maintaining a compression tight gland, and a fear of the consequences should the upper chamber be ruptured in a bad landing. Apart from these, the oleo-pneumatic leg appears to have every advantage in weight, durability, and service.

There are many variations of these systems, which have here been stated in their simplest form. An example is in the Fairey III F, a two-seater, general purpose military aircraft (see Fig. 349). The chassis is of the plain V type with cross axle, as shown in Fig. 319. The landing impact and taxying loads are taken on rubber blocks in compression. There is a big rebound with this material when the load is relieved. In the Fairey leg it is checked on the return by an oleo damping gear. This can be varied to suit local conditions. The leg consists of two tubes sliding one within the other; the upper part carries the rubber buffers, whilst the oil cylinder is in the lower portion. The whole assembly is very compact and lends itself readily to the fitting of a simple fairing.

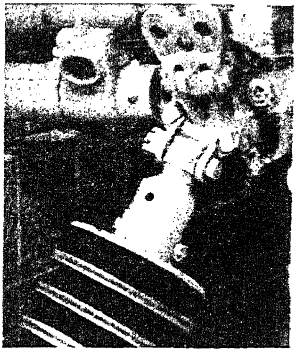


FIG. 349

(By courtesy of "Flight")

A similar but larger unit, from the Short Scylla, is illustrated in Fig. 351. It will be seen that the volume of the oil chamber does not vary and that the piston carrying the relief valve passes through the oil from the bottom to the top as the leg is compressed.

The undercarriage leg of the Vultee V.11 (see Fig. 350) is constructed in a similar way to that shown diagrammatically in Fig. 334.

It appears that a strong box girder carries the fore-and-aft and sideways bending loads. The vertical reaction is taken on the internal shock absorber which is thus freed from bending loads. The cantilever axle is mounted in a heavy fitting which is attached at its top to the oleo and which runs on "V" slides against the front and rear walls of the box girder. This fitting is welded up from steel sheet, but the box itself is constructed from aluminium alloy.

Wheels. There is little in wheel construction which calls for the attention of the aircraft designer, since they are standard articles, produced in three or four proprietary brands. The choice he must make is between intermediate- and low-pressure tyres. The difference between them is illustrated in Fig. 352. Owing to the narrower width and the smaller "spread" of the intermediate pressure tyre which occurs under load, the bending moment of the axle is less.

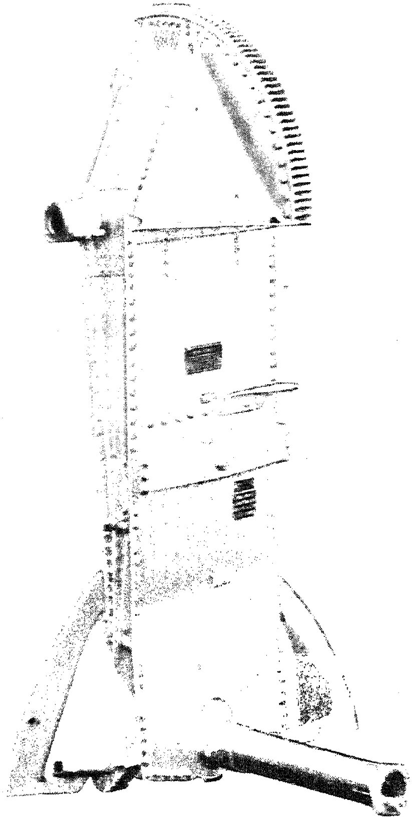


FIG. 356. VULTEE "V-11" UNDERCARRIAGE LEG
(*By courtesy of Vultee Aircraft*)

On the other hand, it is claimed for the low-pressure wheel that, though it is wider, the air drag is less. This type has a special advantage on soft, muddy, or sandy aerodromes, the greater width reducing the pressure on the ground and preventing sinking. Further, it has considerable shock-absorbing qualities, even when punctured.

After trials on all types of aircraft the general tendency now is towards the intermediate pressure tyre as the best compromise between the now obsolete high pressure and the newer low pressure tyres. The growing popularity of wheel brakes has possibly influenced this development since it is difficult to design a satisfactory brake within the small dimensions of the hub of a low pressure wheel.

Take-off time is influenced by wheel diameter, and a poor take-off may be improved by the use of a larger wheel which reduces the rotational speed at the hub.[1]

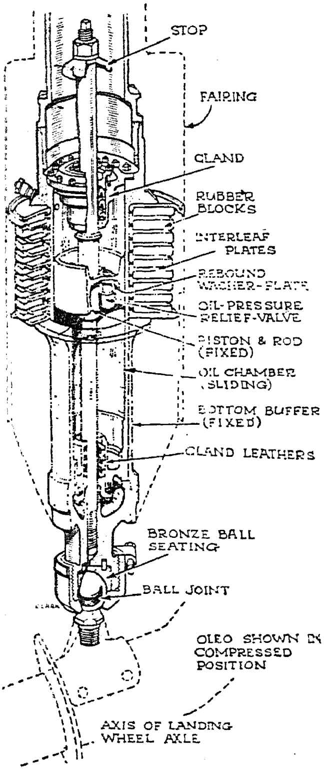
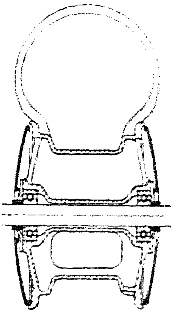
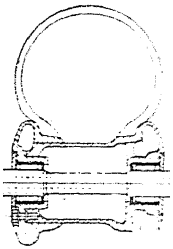

STOP
FAIRING
GLAND
RUBBER BLOCKS
INTERLEAF PLATES
REBOUND WASHER-PLATE
OIL-PRESSURE RELIEF-VALVE
PISTON & ROD (FIXED)
OIL CHAMBER (SLIDING)
BOTTOM BUFFER (FIXED)
GLAND LEATHERS
BRONZE BALL SEATING
BALL JOINT
OLEO SHOWN IN COMPRESSED POSITION
AXIS OF LANDING WHEEL AXLE

FIG. 351. SHORT "SCYLLA" OLEO LEG
(By courtesy of "The Aeroplane")



INTERMEDIATE PRESSURE TYRE



LOW PRESSURE TYRE

FIG. 352

Wheel Brakes. Very definite advantages must be proved for any increase in weight, particularly to a unit already so parasitical as the chassis. Yet the extra weight involved in the fitting of brakes is justified on most aircraft by the fact that they reduce the landing run by something like 50 per cent, thus making a forced landing in restricted space a safer operation.

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[1] For further information see "Wheels and Tyres," by G. H. Dowty, A.F.R.Ae.S., in *Flight* (Aircraft Engineer Supplement), 25th April, 1930, also "Aeroplane Covers and Wheels," by J. Fellowes, *Journ R.Ae.S.*, Feb. 1933.

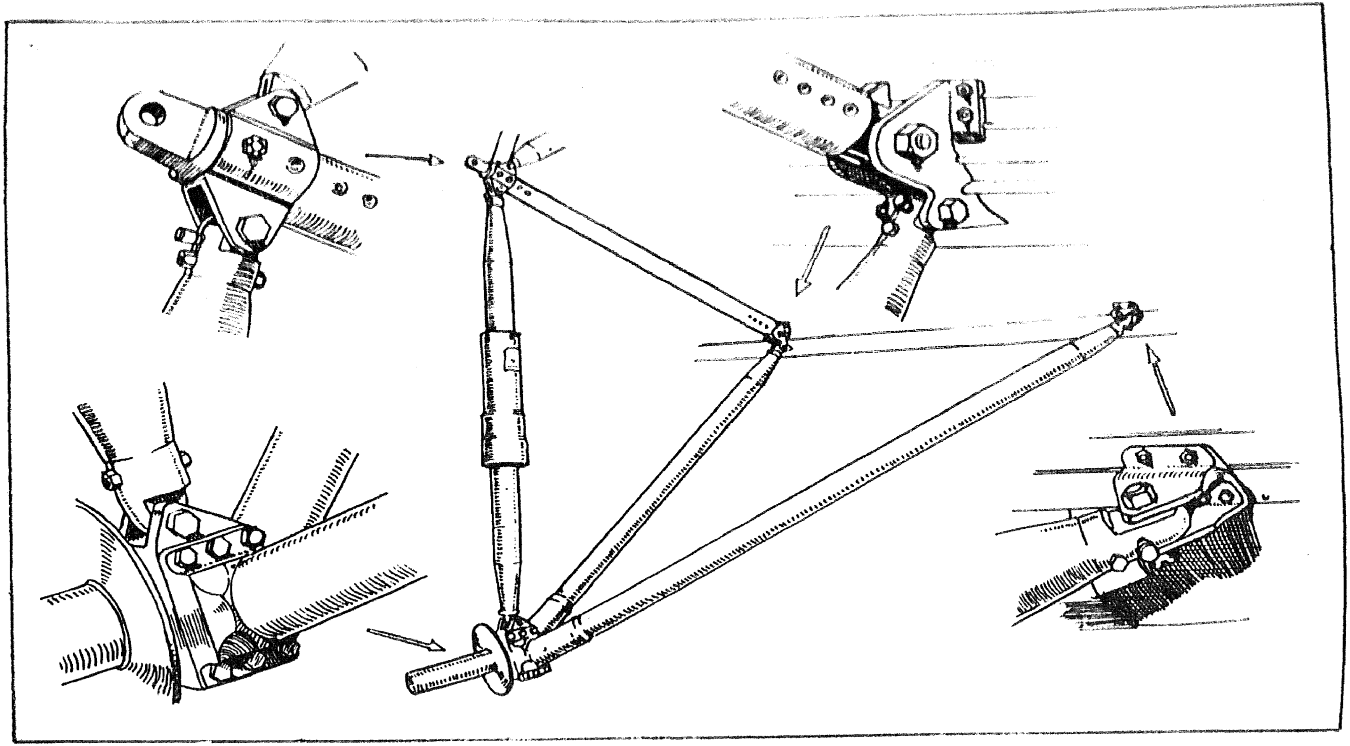

Fig. 353

(By courtesy of "The Aeroplane")

Further advantages lie in the increased control on the ground, particularly in cross-wind taxying and in the smaller ground crew necessary for handling.

Considerable modification is necessary to the ordinary chassis before it is suitable for brakes. The wheels must be thrown forward to such a position that there is no tendency for the aircraft to nose over on touching the ground. If too far forward, however, the load distribution between wheels and tail skid becomes such as to impose severe strains on the fuselage.[1]

The chassis members must be made stronger to carry the additional load which is now placed on them. The friction between the tyre of the locked wheel and ground acts as a moment about the hub or axle centre, creating a torsion in that member. It may be counteracted in a number of ways. The first is that used by Vickers in the chassis shown in Fig. 353.

The brake drum of the wheel is attached to the flange of the axle fitting, which is very robust and holds the ends of both axle and radius rod fixed. In addition to the other loads which these members already carry, they must be stiff enough to resist the bending put on them by the tyre-ground friction acting about the hub centre.

An alternative method of counteracting the torsion is shown in Fig. 326 and already discussed on page 279. The brake drum was bolted to a flange on the axle, the ends of which were squared. These ends fitted into recesses at the ends of the fork but stood proud by a few hundredths of an inch. The caps could thus be pulled up on them to counteract wear. This method as carried out on T.K.2 implies a stout compression strut and a robust anchorage to the wing structure.

The types of brakes used may be divided into two. Both are totally enclosed and have a tyre and rim moving round the drum. Pressure is applied to the rim through friction linings by expanding shoes in the one case and by a flexible annular expansion chamber in the other. As with wheels, the brake design is outside the range of the aircraft constructor, and complete braked wheels are supplied as standard by several specialist manufacturers, such as Dunlop, Palmer, Goodyear and Bendix.

ENGINE MOUNTINGS

There is no standardization in aircraft engine mountings. Three factors account for the great diversity which is found—the engine; the structure, whether fuselage or main planes, to which it is attached; and the position of the engine in relation to that structure.

Engines may be grouped into three main classes for the purpose of designing a mounting—

1. Radial air-cooled—e.g. Pegasus, Jaguar, Whirlwind, Lynx, Genet, Pobjoy.
2. In-line vertical air-cooled—e.g. Cirrus-Hermes, Gipsy, Dagger.

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[1] The estimation of upsetting moments is simple. See the following—

"Wheel Brakes and their Application to Aircraft," by G. H. Dowty, A.F.R.Ae.S., in *Flight* (Aircraft Engineer Supplement), 24th November, 1927; 29th December, 1927; 26th January, 1928.

"Wheel Brake Equipment for Aircraft," by the same, in *Aeroplane* (Aero. Eng. Supp.), 29th August, 1928.

"Aeroplane Braking Systems," by R. [illegible] June and July, 1931.

3. Wate [illegible] with two or three banks of cylinders arranged either in V or [illegible]—e.g. Kestrel, Lion.

In the first group the engine is attached to a vertical circular plate or ring, concentric with the cylinders and crank case. In the second and third groups it is attached to two horizontal fore and aft girders, one down each side of the crank case, parallel to the thrust line. The circular ring or the horizontal girders as the case may be are in turn strutted back to the main structure of the machine.

The method of strutting employed depends on the part of the airframe to which the engine is attached and the members available there for attachment. A further difficulty lies in the clearance which must be given to the back or lower projections of the engine and the accessibility required for such parts as magnetos, carburettors and sparking plugs.

The cases considered for stressing are searching. The first is that of the machine turning in flight with engine on, a combination of loads being assumed as acting. These loads are—

1. Gravity forces;
2. Thrust and torque of the airscrew;
3. Gyroscopic couple.

The first two of these are usually the deciding items, the gyroscopic couple being only of importance when a large heavy airscrew is fitted. Rotary engines caused a load of this kind, but they are now obsolete. The second case is that of normal flight and landing with engine off, the principal load being due to the weight of the engine. In the third case the machine is assumed to be resting on the ground whilst the engine runs, exerting maximum thrust and torque. The loads are therefore considerable in all three dimensions.

Taking first the radial air-cooled engine, Fig. 354 shows the mounting of a *Jupiter* in the nose of a Fokker C-V fuselage. The outer ring and its four struts compose the cowling structure and take no share in the primary engine loads. The inner ring is a continuous steel tube, to which are welded nine channel clips, picking up nine holding-down bolts on the engine. From this ring the mounting structure runs back to the fuselage in two bays with an intermediate transverse panel. The top corner fore and aft members are in tension and the lower ones in compression under the gravity loads. All have tension loads under the engine thrust, increasing the stress in the upper tubes and reducing it in the lower ones. The direction of loading due to torque depends on the sense of the airscrew rotation relative to the diagonal bracing tubes in the horizontal and vertical bays. It is in opposite directions on the port and starboard sides of the mounting. It will be seen that the whole structure is a welded one, similar to the fuselage construction. It is removable as a unit by taking out four corner bolts at the fuselage attachment points. This allows of the whole unit being changed easily. The solid welded-up structure is undoubtedly satisfactory for taking the vibration of the engine. There are no pins to get worn and displaced, and no wire bracing to suffer from fatigue which causes cracking and fracture. The bearing strength of bolts and fittings at mechanical joints of an engine structure should be assumed to be reduced at least 60 per cent from the normal strength of the material.

A mounting for the Wright J.6 radial engine is made up with mechanical joints in the Curtiss *Thrush* (Fig. 355). The tube ends are flattened and the joints made with gusset plates and tubular rivets.

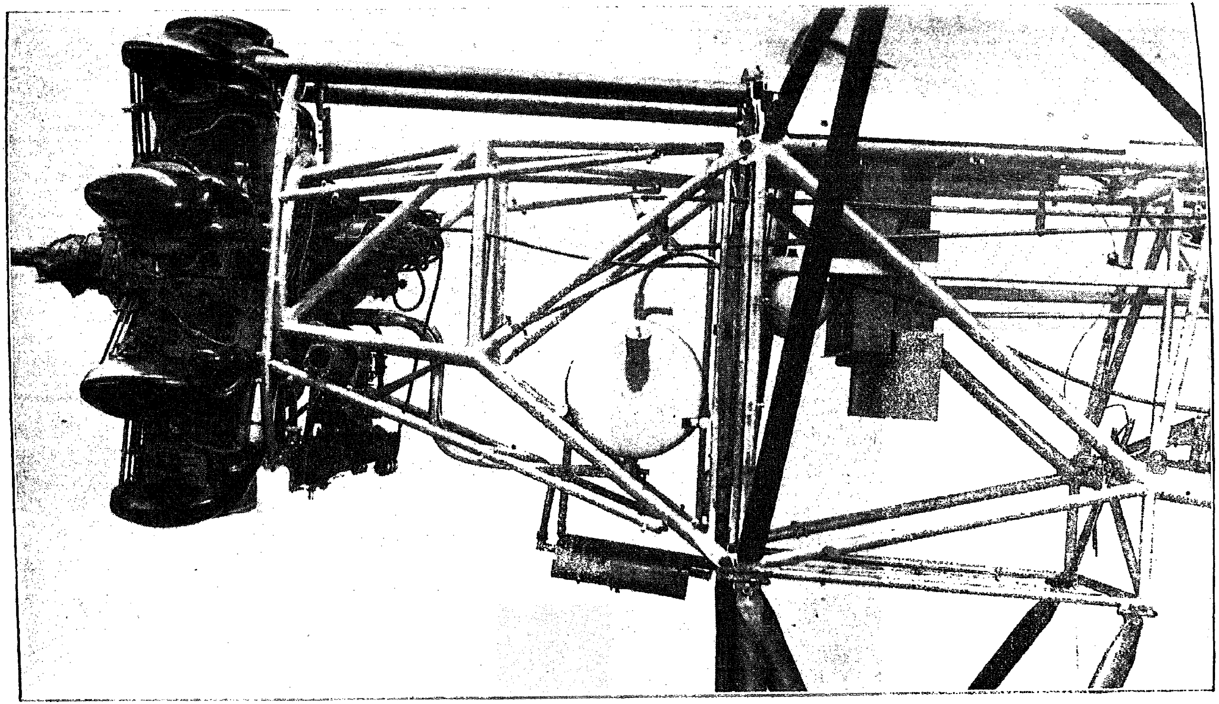

FIG. 354. "JUPITER" ENGINE MOUNTING IN FOKKER C-V
(By courtesy of N. V. Nederlandsche Vliegtuigenfabriek)

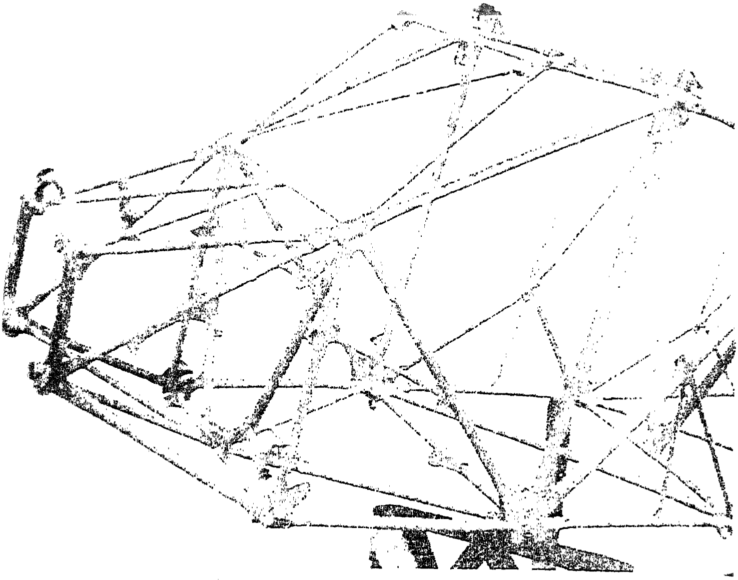

FIG. 355. CURTISS "THRUSH"—ENGINE MOUNTING AND FRONT END OF FUSELAGE

(By courtesy of The Curtiss Aeroplane & Motor Co., Inc.)

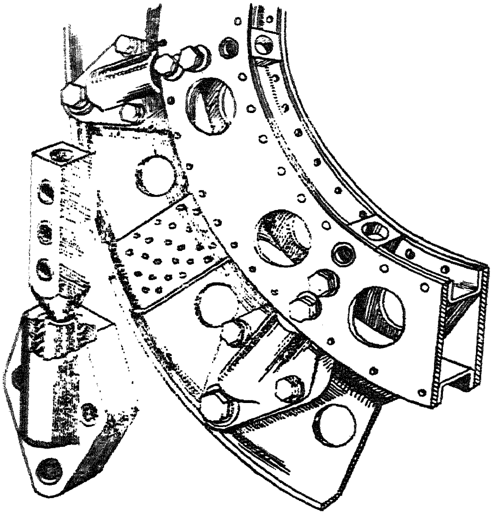

FIG. 356. SHORT "VALETTA" ENGINE MOUNTING DETAILS

(By courtesy of "Flight")

A system of absorbing the vibration in rubber blocks is applied in many aircraft, an example being in Fig. 356, the mounting ring of the

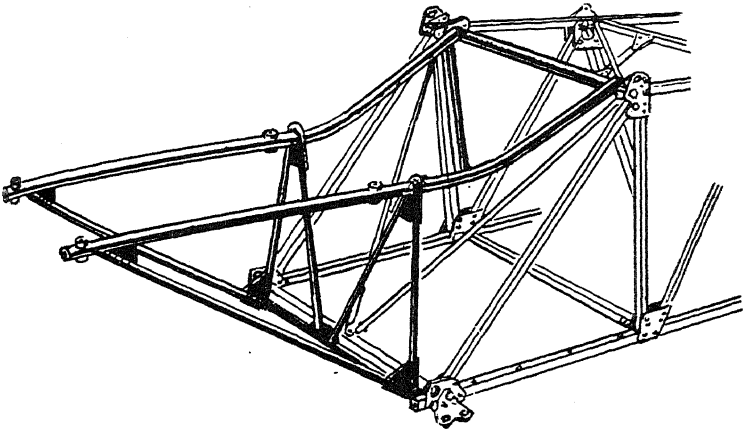

FIG. 357. WESTLAND "WIDGEON" ENGINE MOUNTING
(By courtesy of "Flight")

Jupiter XI.F engines in the Short *Valetta.* This method is useful not only in reducing the fatigue on the surrounding structure, but also in increasing the comfort of the passengers and crew. Proprietary types

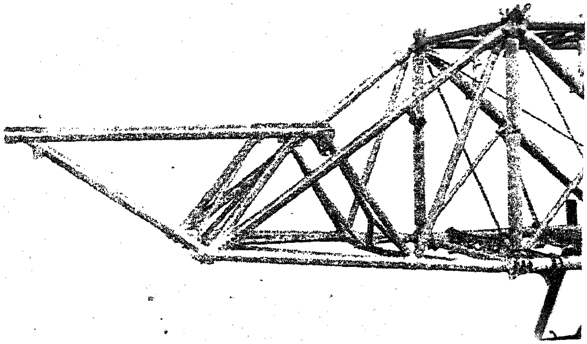

FIG. 358. FAIREY "FOX" ENGINE MOUNTING
(By courtesy of the Fairey Aviation Co., Ltd.)

f rubber dampers are sold under various trade names, such as Dynaflex" and "Silentbloc."

A simple mounting of the horizontal girder type for *Cirrus Hermes* r *Gipsy* engines is shown in Fig. 357, the Westland *Widgeon.* Like the 'okker mounting, this is in mild steel tube, welded. Four vertical olts hold the engine in position, passing down through the bearer es, which are under bending and tension due to gravity loads. The long sloping members to the bottom rear fuselage attachment are under compression from the weight of the engine, relieved during running by the thrust. The torque relieves the load on one side and adds to it on the other. The M-braced cross panel is put in for torque and side load, and the crank case is relied upon to carry the horizontal reaction at the top ends of the bracings.

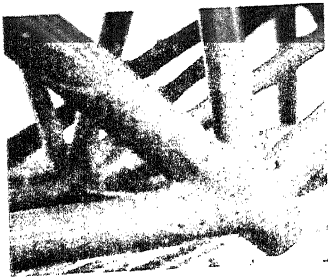

FIG. 359

(By courtesy of the Fairey Aviation Co., Ltd.)

This mounting, as with the previous ones, is attached to the fuselage by four bolts. Not only can the structure be removed to fit another more suitable for a different type of engine, but in the case of a nose-in crash the part most likely to be damaged can be quickly replaced.

An engine of the size and power of the *Kestrel* naturally requires a more robust structure than the just described. The mounting of such an engine in the Fairey *Fo*

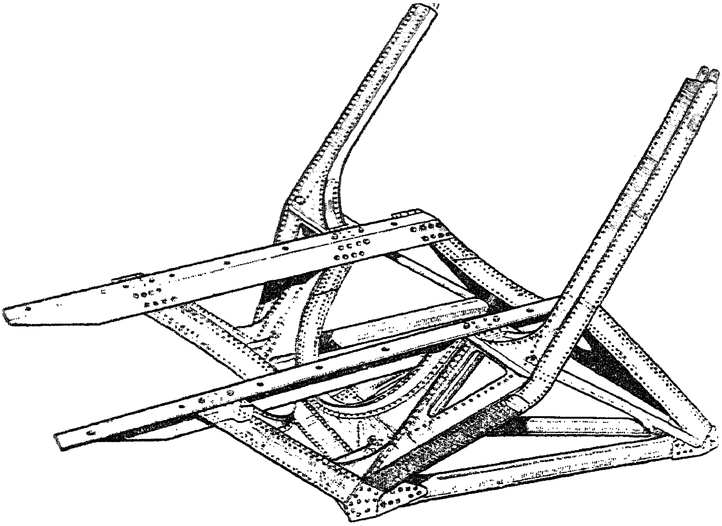

FIG. 360. MUREAUX 170—ENGINE MOUNTING

(*Sketch by J. Gaudefroy, lent by "L'Aéronautique"*)

is illustrated in Fig. 358. The joints are welded, but additional security is given by the welded finger plates and pins at each node. The more heavily loaded members are sleeved at the ends, as will be seen in the detail (Fig. 359). The way in which a sudden change of section is avoided should be noted. In one case the sleeve is "cod-mouthed" and in the other it is chamfered off.

In France it is a common practice to mount engines of this kind on a built-up duralumin structure. Fig. 360 shows the construction of the mounting for the Hispano-Suiza 500 h.p. engine in the Mureaux 170 Fighter. The method of taking the loads is exactly similar to that already discussed. Such a mounting is extremely rigid, and it would be interesting to have comparative weights. It is undoubtedly more expensive to manufacture than the welded type, at least with labour charges as they are in England.

The mounting of a power plant outboard in the wing structure is always more complicated than in the fuselage. The engine, overhanging the leading edge and strutted back to the spars, causes by its weight an up load in the rear spar and a down load in the front one. This relieves the air load in the front truss and adds to that in the rear. The torque, thrust, and "gust" conditions complicate the issue, however, and it is difficult without a detail stressing of any structure to know what the total effect will be.

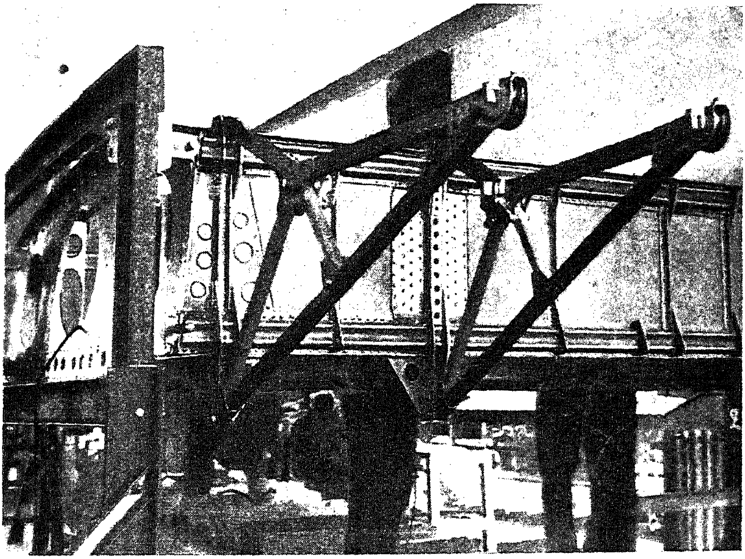

FIG. 361. FIAT G.2—OUTBOARD ENGINE MOUNTING

(*By courtesy of Aeronautica d'Italia*)

When the engines are fitted outboard on a thick-sectioned cantilever monoplane, some such arrangement as is illustrated in Fig. 361 is usually adopted. This example comes from the Fiat G.2. To give the mounting as wide a base as possible, and so to reduce the loads in the members, the horizontal bearer tubes are bent up behind the engine and run to a fitting above the top flange. The lower diagonals are carried well below the spar to points which, although outside the normal wing section, are faired in by the cowling. Between the top and bottom attachment points the spar is stiffened by a vertical channel, and the web carries a large doubling plate with flanged edges attached in the case of the inner bearer with a multiplicity of rivets. The bearer tubes are not solid drawn but built up of channel sections.

A similar form of engine mounting has been developed in Germany by Blohm & Voss (see Fig. 362).

The main side tubes are of aluminium alloy and the fittings are machined from cast aluminium alloy. It will be seen that the side bracing members extend only to the rear engine feet, and that the horizontal tubes are then cantilevered forward. While this means that the bearer tubes must be of large diameter and heavy gauge, it leaves the sides of the engine extremely accessible for maintenance work.

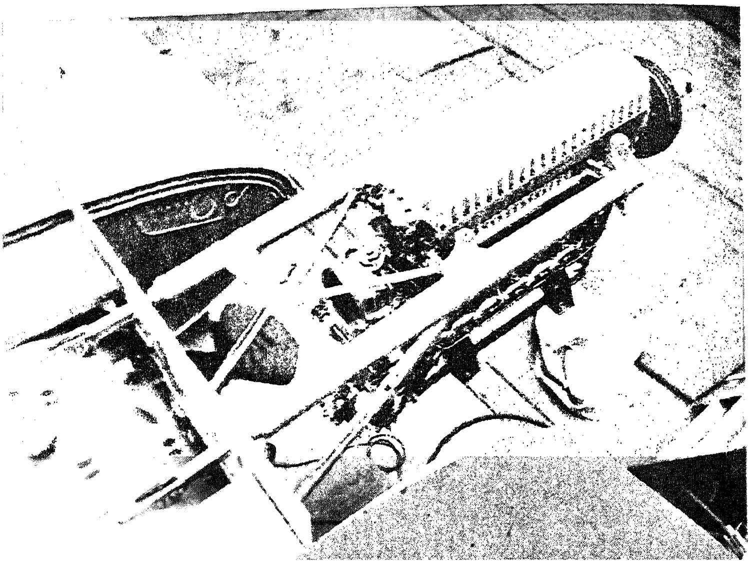

Fig. 362. H.A. "139" Engine Mounting
(*By courtesy of Blohm & Voss*)

A novel form of suspension is used to allow for torsional damping and vertical deflections. One side of the engine is attached to hinges on the bearer tube, whilst on the opposite side there are rubber mountings. The engine thus has a certain amount of freedom around the axis parallel to the crankshaft, but to one side of it, thus movement of the engine itself has only a limited effect on the axis of rotation of the airscrew and secondary gyroscopic moments are avoided. It will be seen that at the rear end the horizontal bearer tubes are anchored back to a tubular spar of the kind described on page 141.

Another German development which is of considerable interest is the engine mounting of the Junkers 87 Aircraft. The main engine bearers are elektron forgings. As in the previous example these are cantilevered forward of the rear engine feet, leaving the cylinders much more accessible than if a completely triangulated structure were used.

The main bearer members are forged as shown in Fig. 364 and this, of course, is extremely economical when large quantities are required.

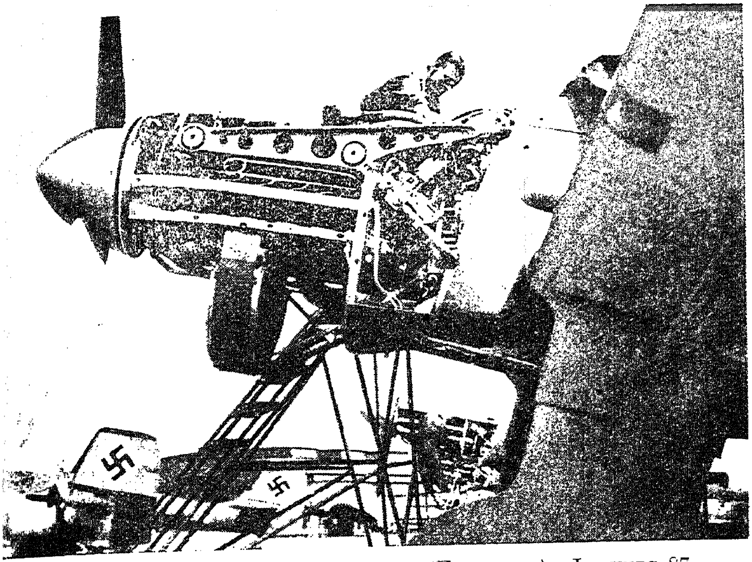

FIG. 363. ENGINE BEARER FORGING (ELEKTRON); JUNKERS 87 MACHINE; JUNKERS JUMO J.U.211 1000 H.P. ENGINE

(By courtesy of Messrs. F. A. Hughes & Co. Ltd.)

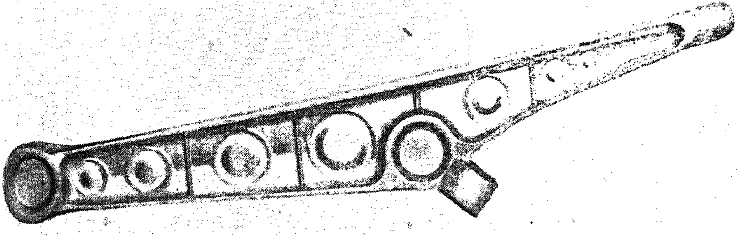

FIG. 364. ELEKTRON ENGINE BEARER

(By courtesy of Messrs. F. A. Hughes & Co. Ltd.)

A comparison between the forged blank and the finished bearer shows that very little machine work is done. This consists only of drilling out the lightening holes, the holes for the two engine feet, turning the rear attachment fitting and milling and drilling the double lug which carries the lower bracing member.

Test specimens cut from a typical forging (which is of elektron alloy AZM similar to the British specification D.T.D. 259) show that the ultimate tensile strength is nowhere less than 18 tons per square inch, and that the minimum elongation is 12·6 per cent. The 0·2 per cent proof stress of the weakest specimen was 7·6 tons per square inch, and the highest 13·3 tons per square inch. The lower proof stresses were found in the immediate neighbourhood of the main bosses.

A further variety of mounting consists of a duralumin monocoque shell with either horizontal girders or a vertical front plate to carry the engine, according to the type used. There may be economy in this, as the monocoque acts also as the cowling or rear end fairing of the engine. The large removable panels necessary for access to magnetos, control adjustments, and so forth, reduce the shell strength considerably and make the method more suitable for a fuselage than for a wing mounting.

A further difficulty lies in dealing with the highly localized loads from the engine feet and transmitting them to points on the wing structure. These difficulties have been overcome in the Short *Singapore III* where tandem "in-line" engines were used. (Fig. 365.) Two parallel bearers run from end to end of the nacelle and diagonal frames, stiffened by the shell plating run up to the strut attachments. In the Supermarine *Stranraer* which was fitted with two radial engines, one in each nacelle, a heavy ring is provided at the forward end to take the engine base plate. (See Fig. 366.)

Both these examples are taken from flying boats where the factories were equipped for handling this type of structure.

FLYING CONTROLS

The flying controls of an aeroplane, though not part of the machine's structure, present in themselves certain structural features which will be discussed here. Questions such as range of movement, differential motions and areas of control surfaces are not within the scope of the present work.

The diagram of controls in Fig. 367 will serve to illustrate many of the points. The ailerons and elevators are operated by hand at the control column *D*. The rudder is foot-operated from the rudder bar *F*.

The cables *A* from the levers on the ailerons pass back over pulleys to a drum at the front side of the handwheel at the top of the control column. In addition, there is a balance cable *B* between the levers on the ailerons, opposite to those connected through to the control column. Turning the handwheel to the left depresses the right aileron and through the balance cable raises the left. This increases the lift on the right wing, and causes the machine to bank over, left wing down.

The control column as a whole rotates in the fore-and-aft sense about hinges on the bottom cross tube. Levers on this tube are connected by cables to corresponding levers on the elevators. Forward movement of the column depresses the elevators, increases the lift on the tail, and forces down the nose of the aircraft. Reversing the motion causes the machine to climb.

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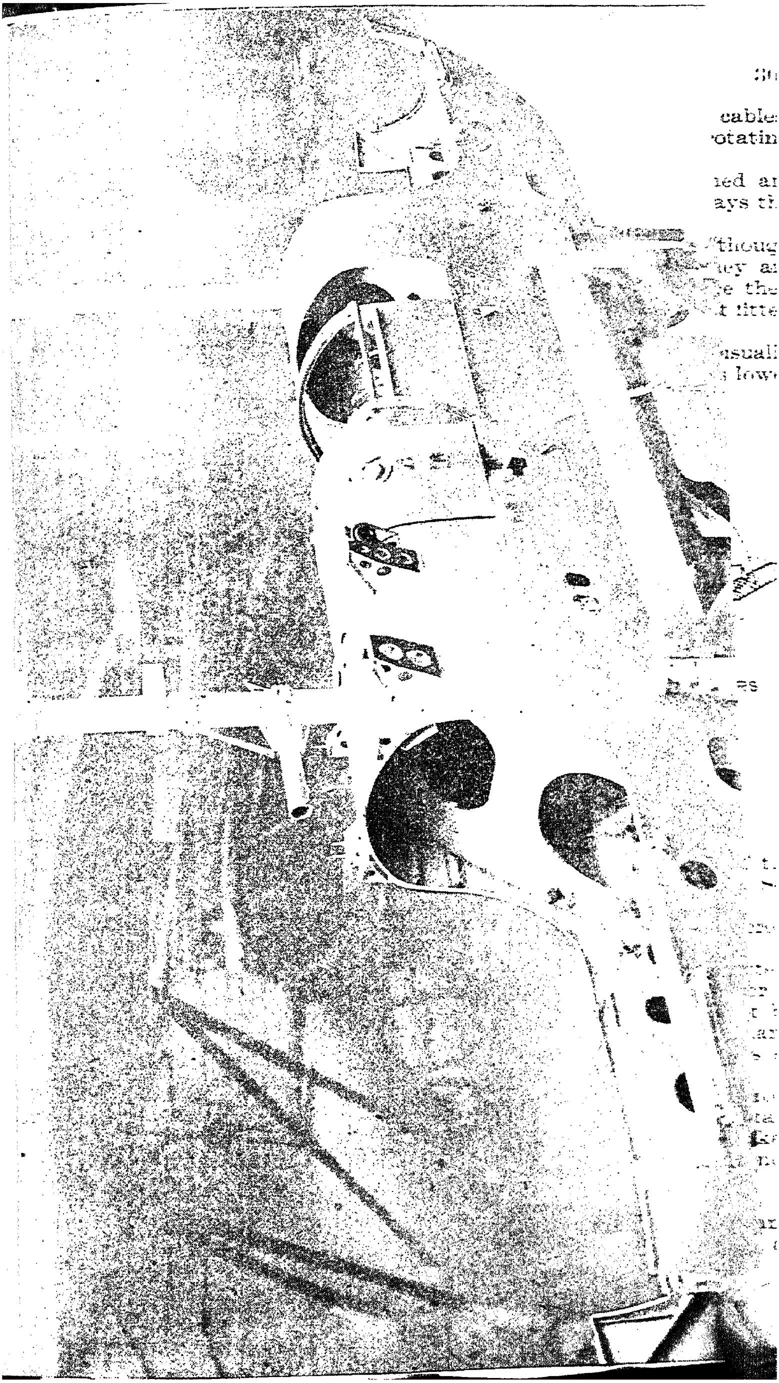


Similarly the rudder bar is interconnected with the rudder by cables. A turn to the left is made by pushing the left foot forward, thus rotating the rudder in a clockwise direction, viewed from above.

Many variations in the details and connections thus outlined are found in different designs, but the directions of motion are always the same.

Pull-and-push rods are frequently used instead of cables. Although heavier and possibly more expensive in their end fittings, they are more durable, do not stretch, and are without backlash. Since they can transmit movement in both directions, double levers are not fitted as with a cable system.

On light aircraft the handwheel method of aileron control is usually replaced by a control column which is universally jointed at its lower end. The aileron motion is then applied by moving the top of the column to the left for left bank and to the right for right bank. See Fig. 371.)

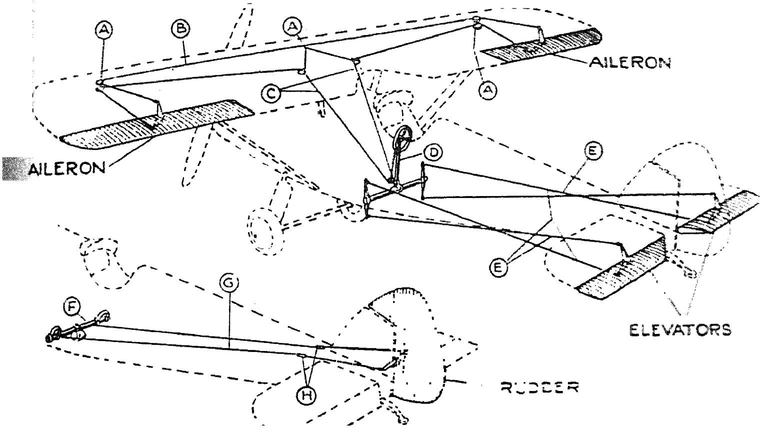


Fig. 367

(By courtesy of "Flight")

Swinging pedals (Fig. 378) are sometimes used instead of a cross rudder bar hinged at its mid point.

The whole system is complicated when dual controls are fitted, whether they be side by side as in most large passenger machines, or in tandem as is usual in training machines. Cross connections must be provided in the cockpit, to reduce unnecessary duplication. In many types of light and training aircraft the second set of controls is so designed as to be quickly removable.

The English method of stressing controls is to work outwards from the maximum loads which could be applied by the pilot. In certain foreign countries the method is reversed and the loads are worked inwards from maximum air loading on the control surface. This tends to give lighter parts than under the English system.

The Control Column and its Connections. Taking first the type of column with handwheel aileron control shown in the general diagram, it will be seen that this may be regarded as a cantilever beam fixed at its lower end. There is a bending moment applied in the fore-and-aft direction due to the operation of the elevators. This is combined with lateral bending when side load is applied to work the ailerons. The aileron control also causes a compressive end load due to tension in one of the aileron cables passing over the drum at the top and pulley at the bottom. If, as in most cases, the drum and pulley are offset, this tension will act as a couple at each end, imposing bending on the column, and augmenting that due to application of elevator control forward. It appears, then, that the resultant bending may be in any direction across the column. A tube is the best form of section to resist such loading, the material being either high-tensile steel or duralumin.

Care must be taken in placing the pulleys for the aileron cables at the lower end of the column. If too high or too low, the application of elevator control will either tighten or slack off both aileron cables together and thus bind the system. An alternative method is to fit bevel gearing at the top of the column, rotating a torsion shaft down the centre, which in turn works a lever or levers at the bottom. Even greater care is necessary here to ensure that the fore-and-aft movement of the column in no way affects the ailerons.

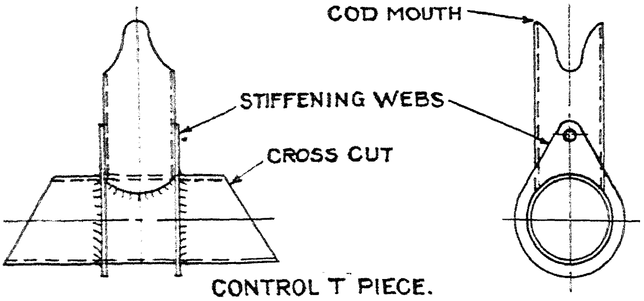


Fig. 368

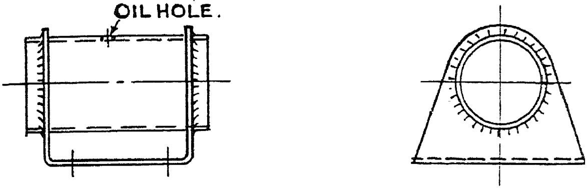
The junction of the column to the bottom cross shaft is made by means of a T-piece, machined, forged, or welded up from tube (Fig. 368). The ends of the T-piece are either cross-cut or shaped in the manner of a cod mouth so that there shall be no sudden change of section. Attachment is made by means of taper pins, rivets or bolts.

Bearings are provided for the elevator lever cross shaft. These may take the form of a short piece of tube welded into a channel plate, which is bolted to the structural frame of the aircraft (Fig. 369). To ensure even movement the bearing should be lined with brass or have short brass bushes inserted at each end and sweated in. An oil hole or grease nipple must be provided in all such bearings. The bearings may be located either at the outer ends of the cross shaft or inside the levers, according to the structural layout of the machine. The reactions of the control loads on the structure at these points must be adequately catered for.

While such examples as these may be appropriate to small-scale production, it is possible to make a much more efficient bearing if the number of aircraft to be built justifies it. For military aircraft produced on a war-time scale one of this sort would be made as a light alloy casting or drop forging. Instead of having brass bearings it would be machined at each end to take ball bearings. The ball-bearing manufacturers have now given special attention to this kind of work and produce lightweight single-race axial bearings specially for the purpose.

The cross shaft will be subject to bending from either or both the loads in the ailerons and elevator cables. It is also under torsion from the latter. A steel tube of fairly high-tensile properties, such as Specification T50 or T45, appears to be the most suitable material from both practical and theoretical standpoints. Workshop difficulties are against the use of as high grade a material as Specification T2.

The levers at the cross shaft ends and on the elevator are regarded as cantilever beams, the relation of their loads to that applied at the top of the control column being in inverse ratio to the lengths. Should the cables, however, converge in plan view, there will also be a lateral load applied at the lever ends.



CONTROL BEARING.

FIG. 369

In small aircraft, if there is no lateral load, the levers may well be made up from thick flat plate. If situated in the air flow they should be radiused off at the leading edge and chamfered steeply at the trailing edge.

To put such levers in the airflow, however, is now an archaic practice and no modern aeroplane has exposed controls.

A typical modern lever is shown in Fig. 370.

This is forged from aluminium or magnesium alloy, the only machining work done on the forging being that of cleaning off the flash and drilling and reaming for the end bearings. Those at the fulcrum are single-row bearings packed with grease and having dust covers. The bearings at the end are of the self-aligning type, allowing a reasonable degree of movement, perhaps 5° to 10°.

Had the column been of the universally mounted kind, there are several ways in which it might have been fitted. One of these is shown in Fig. 371.

For the fore-and-aft motion of elevator control the column is hinged at its lower end and operates the cable lever through a connecting rod. This has universal joints at each end, allowing the column to be rocked sideways for aileron control. The bottom hinge is fixed in this direction and transmits the load to the shaft, which carries it in torsion to the lever at its rear end.

The column is thus under two systems of bending, the one longitudinal with its maximum moment at the point of attachment of the elevator connecting rod. In the lateral sense the column is a cantilever with its maximum bending moment at the bottom. These two

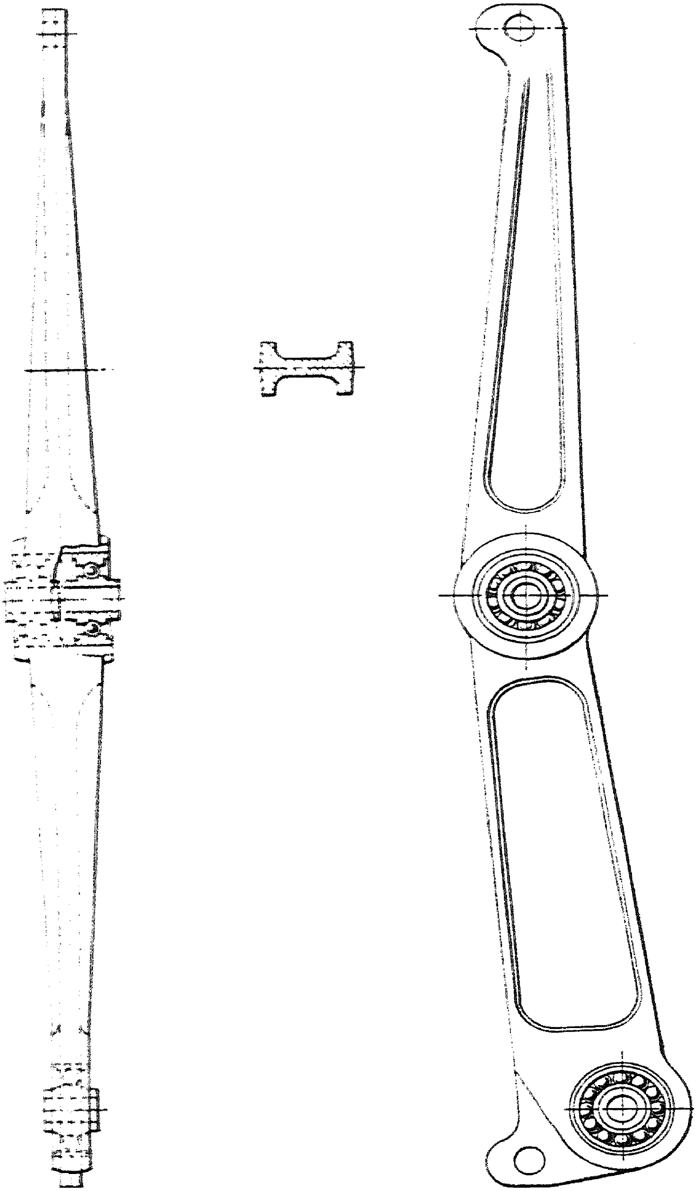


Fig. 370. Forged Light Alloy Lever

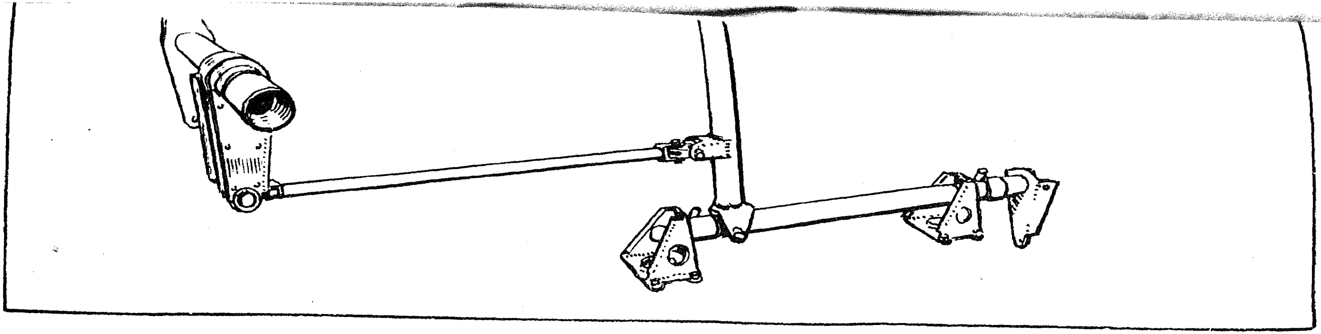


FIG. 371

(*By courtesy of "The Aeroplane"*)

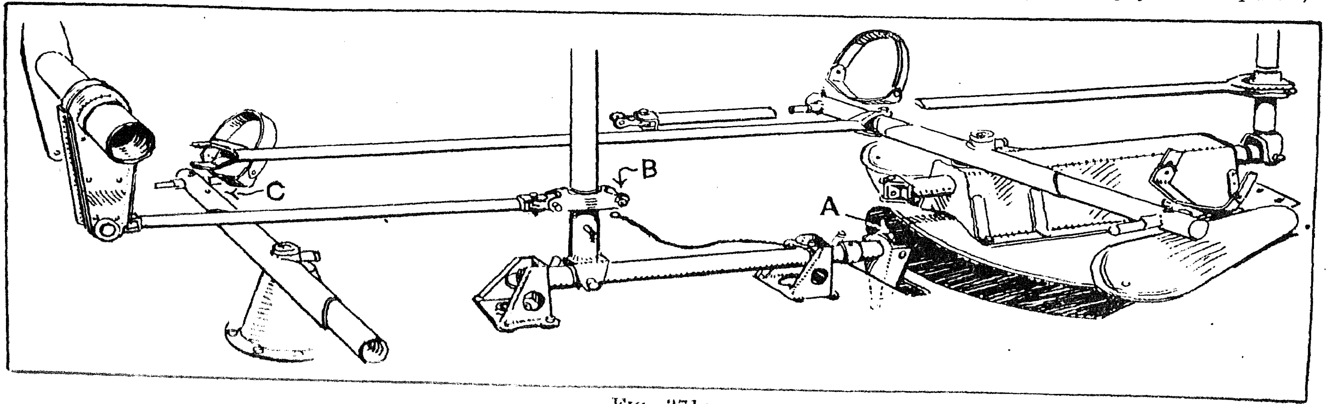


FIG. 371A

(*By courtesy of "The Aeroplane"*)

are combined to give a resultant moment diagonally as seen from above. A combination of this system with another similar one for a dual control machine is given in Fig. 371A, the example being from the Avro 626 Advanced Training Biplane. The controls are shown uncoupled to allow of the removal of the rear set. A connecting rod from the rear column bolts through the fitting *B*, for elevator movement. The torsion shaft for the ailerons is linked up at *A*, and the rudder bar connecting rod is similarly attached at *C*.

The extreme simplicity of all the fittings should be noticed. The connecting rod and control column ends are channels bent up from flat plate and welded in position. The fitting at *B* is a plain channel with the web cut back to allow free movement of the links, these being machined from bar by straightforward milling. The bearings for the torsion shaft consist of a short piece of tube welded into a bent plate box fitting. The use of grease nipples at all bearings may be noticed.

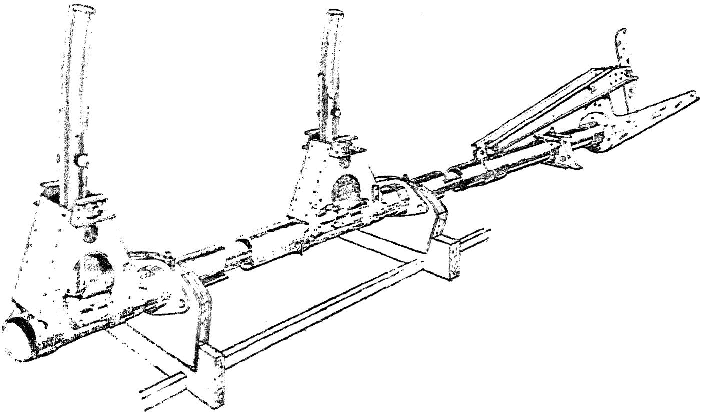


FIG. 372. DUAL CONTROL OF S.M.1

(By courtesy of "Flight")

An alternative arrangement of dual control is sometimes used, and the example shown in Fig. 372 is taken from the Shackleton-Lee Murray S.M.1. The aileron control is transmitted to a large diameter torque tube which rotates in bearings under the front and rear seats. The torque is transmitted to this tube from the control columns through triangular brackets, and the bolts connecting the columns to these brackets also serve as fulcra for the fore-and-aft movement which works the elevators. The elevator control connecting rod, between the bottom ends of the columns and behind the rear column to the lever, passes down the centre of the torque tube. The use of the elevator control causes the connecting rods to rise and fall slightly, in addition to their longitudinal movement and there must be sufficient clearance to allow for this. The torque tube is, of course, slotted in two places to receive the bottom ends of the columns. All the bolts are hollow-drilled for lubrication and have grease nipples screwed into the heads. Either stick may be removed instantly by withdrawing the upper pin in the cod-mouthed sleeve.

The stress distribution, in this type of control column, is different from that in the Avro 626 in that the lateral bending moment, due to aileron control, is taken out in double shear on the upper hinge pin. From there to the bottom of the stick there is only fore-and-aft bending moment due to elevator control.

It is a point of great convenience in assembly and repair if the control unit in the cockpit can be made as a single component put together on

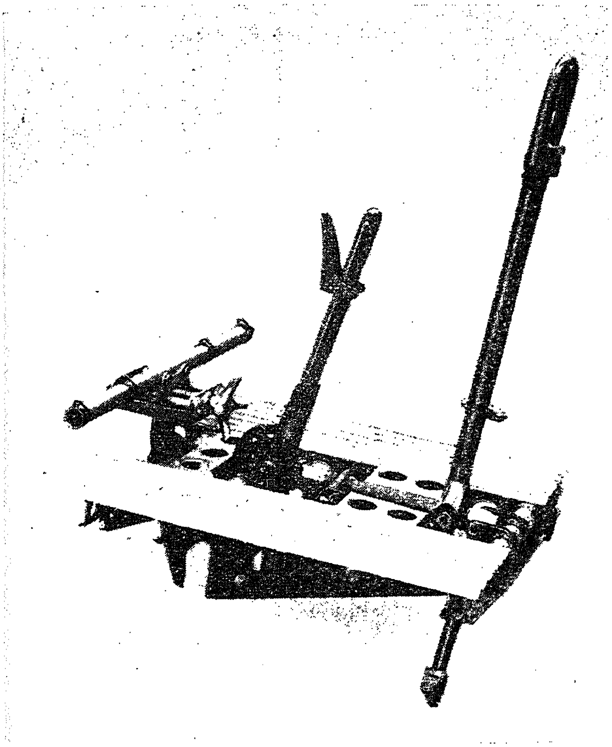


FIG. 373. LETOV CONTROL UNIT

(By courtesy of Letov)

the bench and then assembled as one place in the machine. This is illustrated in Fig. 373, the cockpit control unit of a Letov Fighter. The control column trimming lever and rudder bar are mounted together with the heel slides on a metal frame. The intricate details of the assembly can thus be handled more simply away from the rest of the structure. It is attached to the lower longerons and cross members by four bolts.

A point calling for some ingenuity arises in deciding the run of aileron cables in a machine with folding wings. In order to simplify the folding operation it is undesirable to have to disconnect the controls. An extremely neat method of surmounting this difficulty was adopted in the *[illegible]* (Fig. 374). The wing root hinge at the rear spar is in the middle of the picture. The aileron operating lever from the cockpit passes through the bottom of the fuselage and is linked to a T-crank on the wing root. Double cables from the crank pass into the

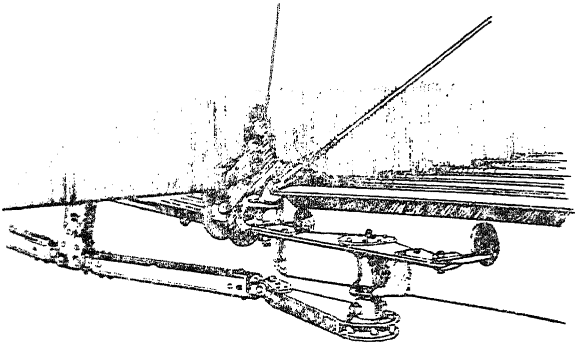


FIG. 374

(*By courtesy of "Flight"*)

wing and so to the ailerons. On folding the wing the ailerons are automatically centred as the pin between the link tube and crank falls vertically under the spar hinge.

In some types of light plane the wings will not fold back snugly unless

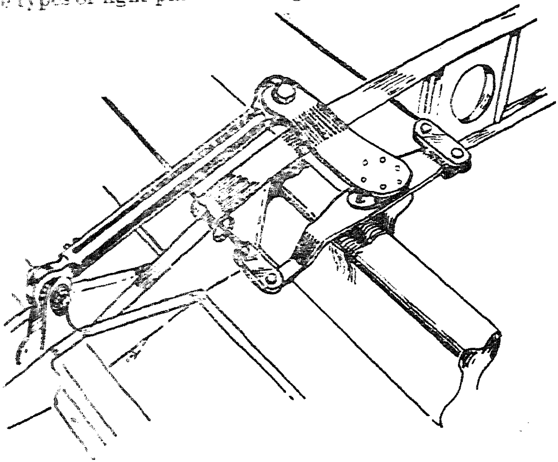


FIG. 375

(*By courtesy of "The Aeroplane"*)

the ailerons droop in the folded position. It is possible so to arrange the run of the control cables in relation to the hinge that the folding back of the wings pulls the ailerons down by slacking off one cable whilst tightening the other.

It is frequently not possible or desirable to follow the extremely simple run of aileron controls shown in the diagram (Fig. 367). Differential motion of the aileron or an objection to the use of cables in exposed positions may suggest some such arrangement as in Fig. 375. In this example the cables are led out along the wing to a T-crank on the rear spar opposite to the operating lever on the aileron itself. An alternative but similar arrangement which is popular is to place the crank between the spars and to substitute a sprocket for the cross lever. Round the sprocket runs a short length of bicycle type chain which is connected by shackles to the cables. This does not appear to have any advantages over the T-crank, which is cheaper and lighter. Further, the weight of the cable and chain tends to cause the latter to drop off the sprocket unless kept very taut. The objection does not arise if the sprocket is turned through 90 degrees into the vertical plane. It is possible to arrange it thus if the wing section is thick and the cable led round pulleys mounted on the front spar.

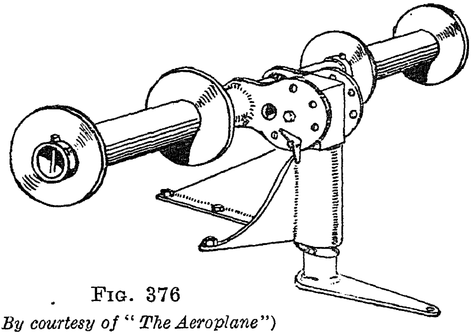


FIG. 376
(By courtesy of "The Aeroplane")

It will be seen that the connecting link between the crank and the lever on the aileron has a small lateral movement in plan view. To meet this universal motion, knuckle or ball-and-socket joints should be fitted, or else a swivelling ball race of the kind shown in Fig. 375.

Fig. 229 illustrates many points of interest in the controls of the Fokker C-V, particularly in detail design.

Rudder Controls. The design of the rudder controls is usually simpler than those of either the elevator or ailerons. Turning again to the diagram (Fig. 367), they will be seen to consist of a cross operating bar with cables passing straight aft to the levers on the rudder. If the difference in level between bar and levers is considerable, it is advisable to break the angle of cable leads by fitting fairleads *H* at some convenient mid-position. The fairlead may be a block of red fibre with the cable passing through a bell-mouthed hole. The block must be split for assembly. If the change of angle is more than 5 degrees, a pulley rather than a fairlead should be fitted. Fairleads may be used on any control cables where there is a long straight run otherwise unsupported. They prevent whipping and damage of the cable or adjacent structure.

The rudder bar, like the control column, is under bending from several directions. The push exerted on it by the pilot is usually neither at right angles to the centre hinge pin nor in line with the cable run, though the differences may be small. Two alternative loadings are specified by the Air Ministry for stress investigations. In the first, the pilot may be pushing on one pedal, the load being resisted by the cable attached at the same side of the hinge. In the second, the pilot will not be operating the rudder, but pressing equally on both pedals.

Constructional details of a rudder bar are given in Fig. 371A. The cables are not in this case attached to the bar itself, but to a separate lever underneath the cockpit floor, connection between the two being through a short torsion shaft which also forms the hinge. The maximum bending moment in either loading is therefore at the centre, and it will be seen that the tube is stiffened with a sleeve over a short length.

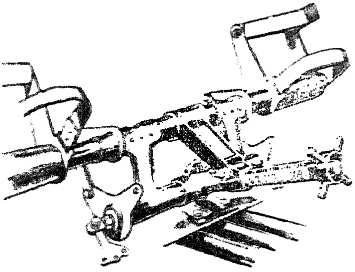


FIG. 377

(By courtesy of "Flight")

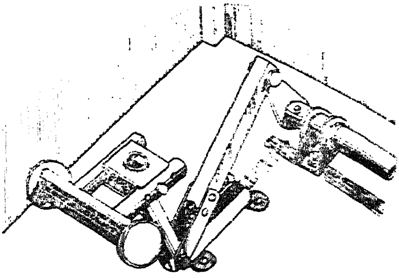


FIG. 378

(By courtesy of "Flight")

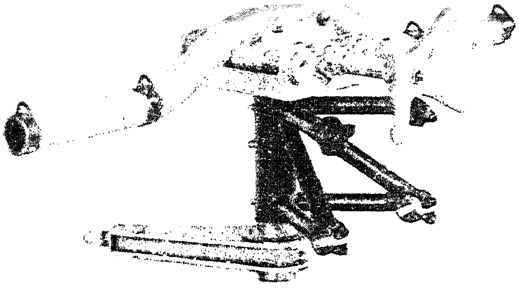


FIG. 379

(By courtesy of Letov)

A method is shown here of making the pedals adjustable. An alternative one is illustrated in Fig. 376.

Another principle is used in designing an adjustment in position for the rudder pedals of the Armstrong-Whitworth XVI (Fig. 377). It is simpler to operate than the example given in Fig. 376, but at the expense of a small extra weight. A cross tube runs between the actual pedals, and this is linked by two cranks to a lower cross tube, at the ends of which are attached the operating cables. The upper tube, and with it the pedals, may be rotated about the lower one by means of the adjusting screw which projects backwards towards the pilot.

A slightly different arrangement is used in the Letov fighters.

The rudder bar is mounted on parallel slides in a box and can be adjusted backwards and forwards on these by means of the operating handle. This can be worked either by the pilot's hand or foot, since it is fitted with large prongs. The box is mounted on top of a spindle which passes through a greased bearing to a lever under the floor. (See Fig. 379.)

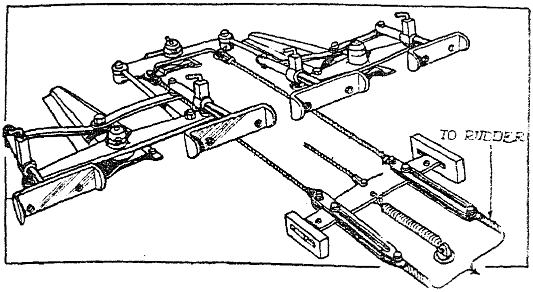


Fig. 380

(By courtesy of "The Aeroplane")

The friction clips for holding the bearing to the frame-work are clearly illustrated. Refer also to Fig. 373 for the complete unit.

Where side by side seating is fitted in a dual control machine, weight may be saved if the two controls are run into one in the nearest possible position. A method of doing this is shown in Fig. 380, the rudder controls of the de Havilland Hornet Moth. This gear has a number of refinements. The pedals are adjustable for length and have on their front sides a parallel link motion which keeps them always square to the foot. The wheel brakes in this machine are operated from the foot pedals and can be put in or out of action by a hand lever on the cabin side. When not in use the rudder cables operate independently of the brake lever through the slots shown. When the brake lever is pulled forward to the front end of the slots it is then put into operation.

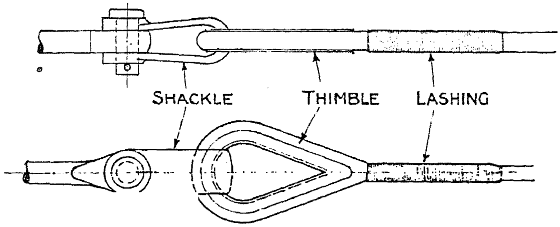


Fig. 381

A practice much followed in America and used in England when the space is small is to fit hinged pedals independent of each other, rather than a cross bar. In the *Redwing*, an English two-seater light aeroplane, each pedal was fitted at the top of a swinging vertical tube hinged below the cockpit floor (Fig. 378). From this ran a link to a torsion cross shaft which was connected to the rudder. The pedal lengths were made adjustable in the orthodox manner.

Cables and Connecting Rods. Control cables inevitably stretch. There is no danger in their stretching. The fact must be accepted and provision made for it. The greatest amount is always noticed in the first few hours' flying.

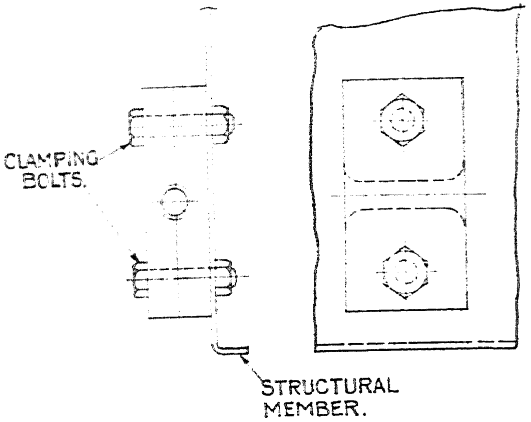


FIG. 382

It is frequently the practice to hang the cables with weights before assembly. This is not sufficient, and, whatever else is done, there must always be a turnbuckle assembled in an accessible position in each piece. This also serves the purpose of allowing a small tolerance on the length of the cable in making up.

A further precaution lies in the use of a heavier size than is dictated by strength requirements. Even though the load be of the order of only a hundred pounds, the smallest size fitted should be 10 cwt. cable. A "stretch factor" of 2 or 3 is always advisable, and adds very little to the total weight.

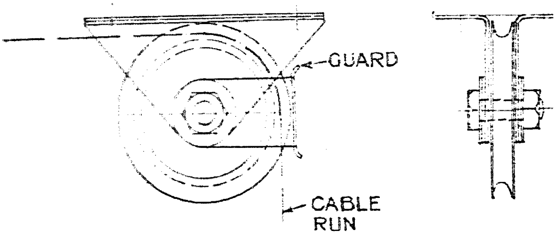


FIG. 383

It was frequently the practice at one time to splice cable ends straight on to the eyes of turnbuckles, levers, and other such fittings. It has been found, however, that the introduction of a shackle at these points much simplifies replacement and maintenance (Fig. 381). The use of fairleads to prevent whipping and to take small angles in change of direction has already been dealt with. The design is simple (Fig. 382) the material being red fibre. The mounting for a pulley requires little comment. It consists of two angles back to back, between which the pulley runs. The angles are spot welded to a base plate (Fig. 383). An important point is to prevent the cable jumping off in whipping or springing back. The jaws of the fitting should be no wider than is necessary to accommodate the pulley. Guards must be provided at the points where the cable enters and leaves it. In the example shown, the back plates act as guard at one side and are brought close up to the rim of the pulley. On the other side a guard plate of thin steel is added. The test of the efficiency of a guard is that it must not be possible by any manipulation to force the cable out of the groove. The danger of fouling in flight will be fully appreciated.

The value of connecting rods instead of cables is debatable, some designers holding entirely to one, some to the other. The more general view, however, is that each type has its uses, cable being preferable for the long open connections down the length of a fuselage or along a wing, whilst tubes are used for shorter links in exposed or cramped spaces. Connecting rods with channel and ball race ends have been shown in Figs. 371A and 375. It is sometimes necessary to make the length of the rod adjustable to suit rigging requirements or erecting tolerances. The standard method is to machine a fork end with a screwed shank. A socket is turned to fit the tube end, and tapped down sufficient threads. There is a further plain portion of socket through which the attachment is made to the tube by weld holes or taper pins. If the latter are used they must be far enough away from the tube end to clear the fork end in its extreme inward position. A lock nut is usually added to hold the fork end during assembly and maintenance operations.

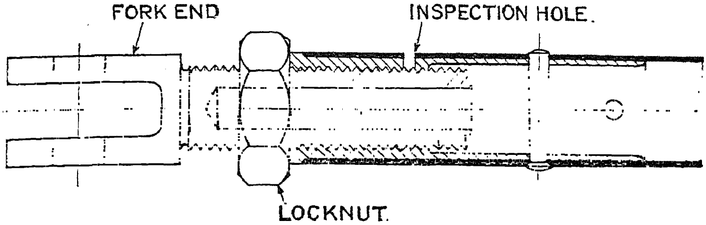


FIG. 384

The control examples given above in general show solid bearings. There is a growing tendency, however, to supersede these by ball bearings, particularly since the ball-bearing manufacturers have paid special attention to the needs of the Aircraft Industry. At one time it was not possible to get bearings of sufficiently light weight to make their use worth while for aircraft controls. In America, however, the Fafnir Bearing Company began to introduce special bearings for aircraft purposes and the big European manufacturers have now followed up the lead which was given them.

The fork end shown in Fig. 384 might now be designed like those of Fig. 385.

This example is taken from the engine controls of Northrop Aircraft.

In such a job it is possible to standardize on perhaps one size of ball bearing throughout the whole run of the controls, and this allows equal standardization of the push-rod end fittings. Instead of using fork ends, however, these fittings must be all off-set if ball bearings are used. The bearing in this case is self-aligning. It is packed with grease and made dustproof by side covers.

It will be seen that the hinges of the bell cranks also have ball bearings, which are dropped between the bell crank itself and a cup fitting which is riveted to it. This cup fitting is machined from bar and is made a tight fit both on the diameter and thickness of the outer race.[1]

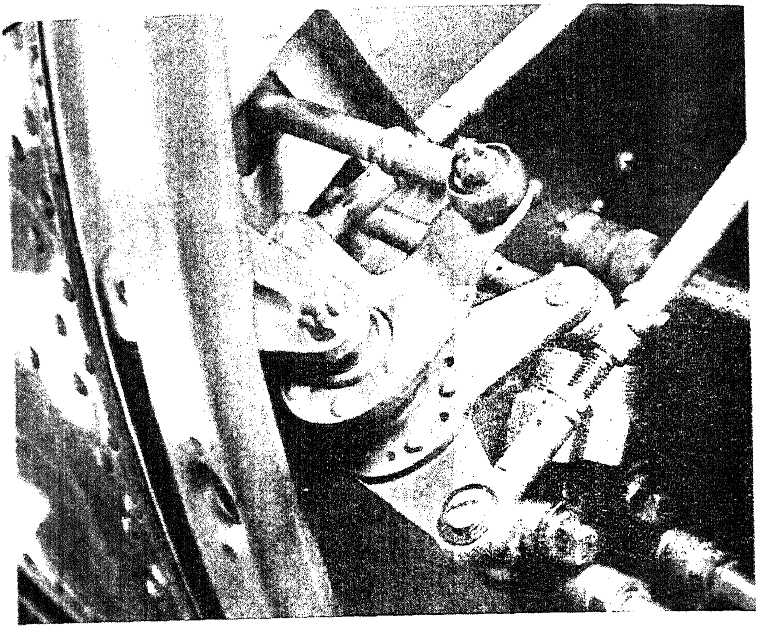


FIG. 385

(By courtesy of the Fafnir Bearing Company)

Flaps. The operation of the trailing edge flaps is completely independent of the main flying controls. Whereas the rudder, elevators, and ailerons are in constant use from the start of a flight until the end, the flaps are only used for certain specific purposes. They serve to increase the lift of the wings when the aircraft is flying at a low speed, and in addition they may, on certain occasions, be used to increase the drag.

They are, therefore, operated by a completely separate control. In some machines this takes the form of a hydraulic pump, and in others of small size the flaps may be raised and lowered by means of a hand lever. The pump handle or the hand lever is usually placed on one side of the pilot's seat.

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[1] For tolerances and fits on such parts see *Handbook of Aeronautics*, Chapter 3, on "Construction."

In the Bristol *Blenheim*, the split trailing edge flaps are in two parts on each side, the inner part in the centre section stub wing and the outer part lying between that and the aileron. They are of flat "Alclad" sheet with flanged ribs.

As will be seen in Fig. 386, they are operated by a tube which travels parallel to the trailing edge, by means of a bell crank lever. As it moves it works a series of links which lower or raise the flaps. Each link is attached to a rib by means of a universal joint, and to the operating tube by a sleeve, which is retained endwise by collars.

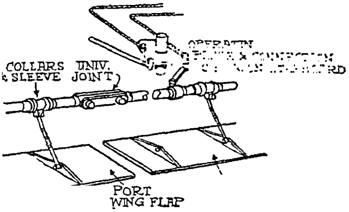


FIG. 386. BRISTOL "BLENHEIM" FLAP OPERATION

(*By courtesy of "The Aeroplane"*)

In the de Havilland *Albatross*, either split or slotted flaps may be provided. The method of operation is shown in Fig. 387.

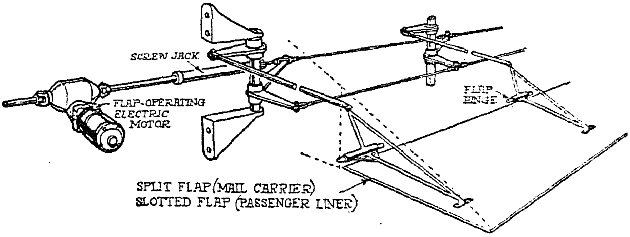

SCREW JACK
FLAP-OPERATING ELECTRIC MOTOR
FLAP HINGE
SPLIT FLAP (MAIL CARRIER)
SLOTTED FLAP (PASSENGER LINER)

FIG. 387. DE HAVILLAND "ALBATROSS" FLAP OPERATION

(*By courtesy of "The Aeroplane"*)

An electric motor is used to provide the power and this turns a screw jack on either side of the fuselage. Inward movement of the jacks lowers the flaps by means of a series of bell crank levers which are interconnected by parallel links.

The operation of a Fowler flap is more complicated since that type not only moves downwards, but also backwards at the same time. In the Lockheed 14 aircraft, the system is as shown in Fig. 388.

At intervals the flap has a strong rib which carries two rollers, one at the leading edge of the flap, and one above the top surface at about the mid-chord. These rollers run in cranked tracks which extend behind the trailing edge, being enclosed in faired housings. The flaps are lowered by a cable which passes back over a pulley at the rear end of the housing. They are raised by a return cable which goes straight forward.

TANKS FOR PETROL, OIL, AND WATER

The design and stowage of tanks present a number of problems which must be roughly decided in the first conception of a machine and definitely fixed at a quite early stage in the drafting. Provision must be made in the most convenient positions, compatible with the capacity required and the structural design, to contain fuel, oil, and water too if the engine is water-cooled.

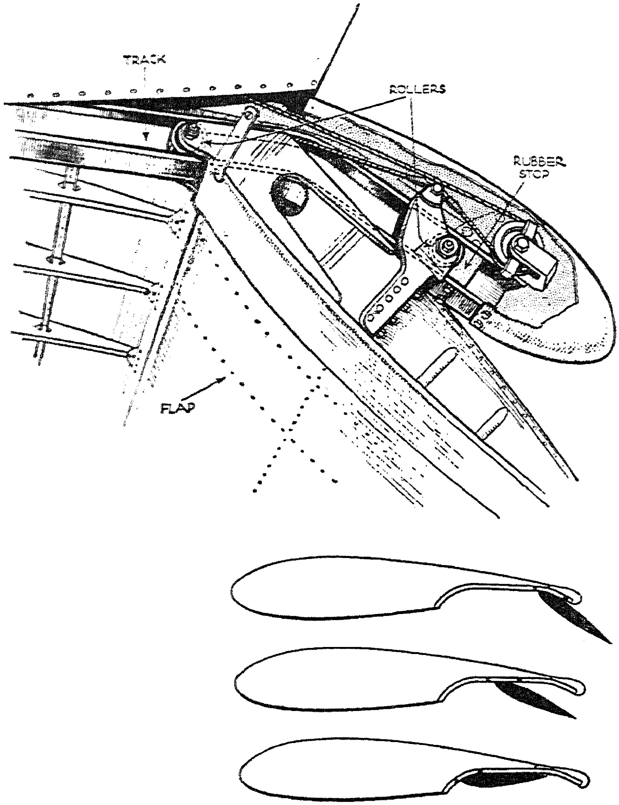


FIG. 388. LOCKHEED "14" FOWLER FLAP

(By courtesy of "Flight")

The most common practice is to carry the fuel tanks in the wing, preferably the upper one if the machine is a biplane. In this position they ensure a gravity feed to the engine, and the complication of a fuel pump is eliminated. Further, the risk of fire is greatly reduced, not only because of the distance which separates the petrol from hot parts of the engine, but also because the tanks are less likely to be damaged if a bad landing is made. The weight of fuel and tankage supported on the spars and acting downwards counteracts the upward air load. For the purposes of stressing, however, the empty weight of tanks may be taken, since they will be approaching that state towards the end of any long flight. On the other hand, when the aircraft is landing, the weight of full tanks may impose a heavy stress in the spars. This case should be investigated.

At one time the fuel was frequently carried in the fuselage, even though a small gravity tank was fitted in the top plane, through which to feed the engine. The fumes escaping through the vent were liable to be troublesome, if not dangerous. It may be said that petrol is now always taken in wing tanks except when the required capacity is far in excess of what may economically be accommodated there. Examples of such cases may be found in thin-winged high-speed fighters and in exceptionally long range aircraft.

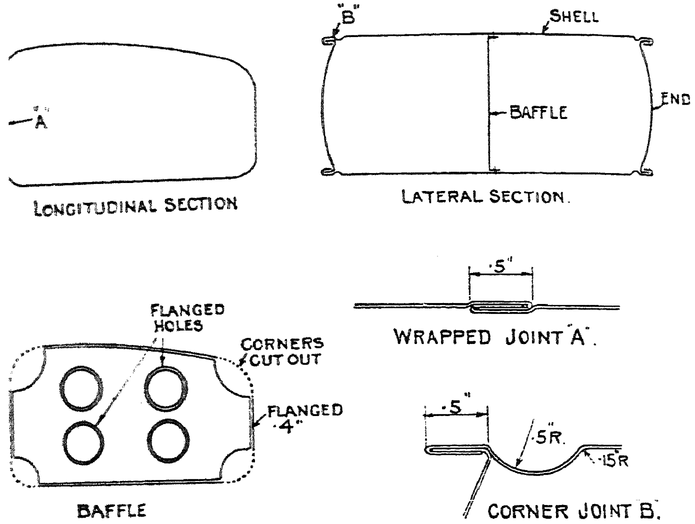
The most efficient shape for a tank—that is, the shape which contains the [illegible] volume for the smallest weight—is a sphere. Practical considerations prevent the use of a globular tank, and a compromise must be made. As far as possible, the longitudinal shape should conform to the wing section. This may lead to a big area in plan view with a comparatively shallow depth. Such a tank may be heavy and interfere unduly with the internal wing structure. In as far as the structure is concerned, the most convenient situation for fuel would be in the leading and trailing portions of the wing. The objections lie in the uneconomical shape and the difficulties of supporting the weight. Tanks are, therefore, usually placed between the spars in the centre section or outboard near the engines in multi-engined aircraft. Attention must be paid to interference with the cross drag bracing which has to be cut out to make way for tanks, and some means of carrying the drag load must be provided. Some designers have made the tank itself part of the structure, the shell being stressed. This method is referred to on page 340. Another method is to fit tubes from side to side, through which the bracing wires are threaded. Such an arrangement calls for an exactitude in dimensions which is extremely expensive to achieve. A third method used in biplanes, is to remove the drag bracing from its usual position at the mid-depth of the spars to the lower surface of the wing. This, though not without objections, is the commonest method. The bracing is, of course, only lowered in the particular bay or bays involved.

The number of tanks and the capacity, dimensions, and shape of each having been decided, the next question to consider is the material to be used. Several are available, such as tinned steel, aluminium, brass, copper, duralumin, and magnesium, and each calls for its own methods of working and jointing. Tinned steel, aluminium, and duralumin are the most used, and these will be dealt with individually. In the first, the joints are made by folding the seams and sweating; in the second, by welding; and in the third, by riveting. Brass and copper, although of about the same weight as tinned steel, are weaker and more expensive materials. The latter, owing to its malleability, is sometimes used for making the domed and beaten parts of tanks otherwise built in tinned steel.

Magnesium, in the form of elektron alloy, is another material which has more recently been used for tank manufacture. The most suitable form is made to the Air Ministry Specification D.T.D. 118. It has a slightly higher tensile strength than aluminium, and may be welded. The construction is similar to that of aluminium tanks, but larger radii should be allowed in the bends to prevent cracking. Some notes on its use are found on page 336.

Tinned Steel Tanks. Although aluminium has every advantage in weight over tinned steel, the latter is still a very popular material. A number of reasons contribute to this favour. Tinned steel is cheaper, and tanks made of it are not only less liable to crack, but if they do they are more easily repaired in out-of-the-way places, tinsmiths being more common than aluminium welders.

Small steel tanks are usually made with a 24 s.w.g. shell. In a larger one the thickness may be increased to as much as 20 s.w.g. The scantlings, however, do not go up in proportion to the tank size. The strength is increased rather by adding stiffeners, corrugations, and baffles. The sides and bottom should not have large unsupported areas, which would pant or distort under load. Distortion is not troublesome so much in itself as in its effect on the seams and joints, tending to make them open and leak.



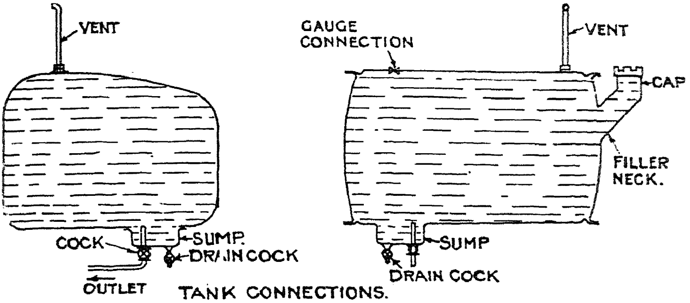
TINNED STEEL TANK CONSTRUCTION.

FIG. 389

Taking as an example a wing tank, the method of manufacture would be as follows (Fig. 389). The shell is first developed flat and then bent round to the longitudinal section of the tank. The corner radii should be as ample as possible. The wrapped joint *A* is then made and sweated up. The width of joint need never be more than 0·5 in., and 0·4 in. is preferable in small tanks. It may be found that the steel plate required is larger than can be made from a single standard sheet. A second wrapped joint is therefore required in the side opposite to the first. Holes are now cut to take the fittings, which will be described later.

The next process is the making of the baffle and ends to a template of the longitudinal section. They may conveniently be made together if the contour is the same for all. The corners of the baffle are cut away, not only because it is difficult and unnecessary to flange the plate round the radii, but also to allow the petrol to flow through. The object of the baffle is only to impede swilling of the petrol, not to isolate it. The baffle also serves to stiffen the shell. As many and as large lightening holes as possible are now stamped in the baffle, these being flanged for stiffness. The baffle is sweated in its correct position and attached with copper rivets $\frac{3}{32}$ in. diameter at 1·5 in. pitch.

The tank ends, after being flanged, are beaten to a slight camber to prevent them panting under pressure. The corner joints are made as shown in *B*. Rivets are not necessary here. They might even induce



TANK CONNECTIONS.

FIG. 390

leaks. The joint is well sweated up, the internal pressure helping to keep it tight. The function of the swage is not only to locate the end and prevent it slipping inwards during making; it also serves to prevent leaks by stiffening the shell at a point where there is a tendency for the joint to open. The width of the double lap should be 0·4 to 0·5 in., not more, owing to the difficulty of folding back the outer shell. The tank described would be of about 30 gallons capacity, 12 in. deep by 24 in. wide. Larger tanks and those of more complicated shape would require more baffles. There should never be more than 3 to 4 sq. ft. of flat surface unsupported.

The minimum fittings required are—

1. Filler.
2. Outlet, with cock.
3. Vent pipe.
4. Sump.
5. Drain cock.
6. Gauge connection.
7. Support fittings.

Extras include such refinements as a hand hole for cleaning, and a jettison valve for quick emptying of the contents in case of imminent danger.

The position of the filler neck is important, since it fixes the amount of petrol which may be put into the tank. Account must be taken of the normal attitude when the filling is done—that is, tail down on the ground. The filler neck may be made in the form of a tinned steel

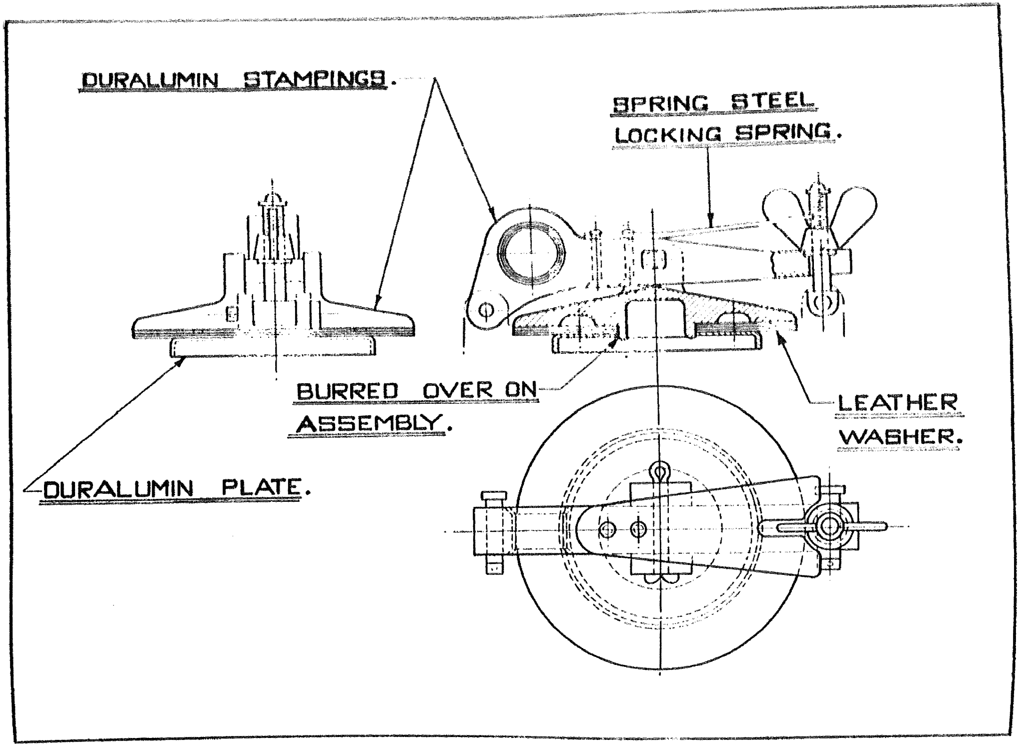

DURALUMIN STAMPINGS.
SPRING STEEL LOCKING SPRING.
BURRED OVER ON ASSEMBLY.
LEATHER WASHER.
DURALUMIN PLATE.

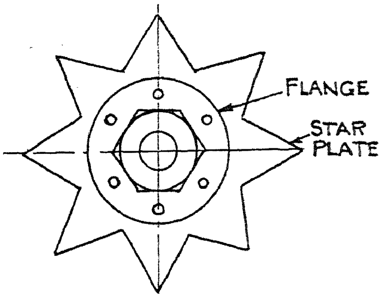
FIG. 391

(By courtesy of The Gloster Aircraft Co., Ltd.)

tube with a narrow wrapped joint of the kind already described for the tank shell. It is either flanged at its lower end or has an angle riveted on. The neck is then attached to the tank with copper rivets. The cap and seating normally used in England are standard brass parts to A.G.S. 607 and 609. In some cases it may be possible to dispense with the neck and fit a cap seating to A.G.S. 608 direct to the tank shell with copper rivets. It is not desirable to interfere with the air flow over the upper wing surface, and the neck type of filler allows this to be kept flush.

Many other types of filler cap are used and that designed by the Gloster Aircraft Co., Ltd., is a good example (see Fig. 391). Its advantage over the A.G.S. type is that wear and damage of the thread which holds the cap down need not affect the petrol-tightness of the cap, the small bolt being easily replaced. Further, it is probably slightly quicker and easier to screw and unscrew. The spring locks the butterfly nut by engaging one of its wings and is easily pressed down with one hand whilst screwing the nut with the other. By anchoring the cap back on to the top of the filler neck the pressure is localized round the rim of the neck where it is needed.

The vent pipe, drain cock, and outlet pipe are all coupled on to female flanges (such as A.G.S. 629, 630) riveted to the tank. Male flanges might appear more convenient, but their use was discontinued owing to the possibility of damage to the exposed thread and the difficulty of replacing a damaged part riveted to the tank. The size of these flanges depends in the case of the vent and drain cock on the size of the tank. A common size of the former is $\frac{1}{4}$ in. B.S.P., and of the latter $\frac{3}{8}$ in. B.S.P. The outlet pipe is decided by the requirements of the engine, but is usually about $\frac{1}{2}$ in. B.S.P. There should be an extension on the supply inwards up to the level of the sump top so that such dirt as accumulates in the sump may be drained off and will not enter the engine line. It is usual to fit a stop valve to the supply pipe immediately on the outside of the flange fitting, thus making for ease in removing a tank containing petrol.



STAR PLATE DOUBLING.

Fig. 392

The sump may be either made up from tinned steel or, if small, beaten in one piece from copper. The tank shell must be stiffened up in the way of all fittings, flanges, etc. In order that any stress may not be localized, a star plate should be sweated to the tank wherever fittings occur. An example is shown in Fig. 392.

A variety of methods may be used for supporting the tank. A simple and effective one is to sweat and rivet shallow channels to the shell into which can seat steel or duralumin straps or slings. It should be remembered that the weight of the tank may act in any direction, depending on the attitude of the machine. Another method is to rivet and sweat robust fittings on to the shell through which fixing bolts may be put, attaching the tank to its supporting members, whether these be the spars, drag struts or special cradle. Any kind of rigid mounting is likely to give trouble, and there should always be some resilient points in the supports, preferably making use of rubber buffers. Star plates and baffles should be arranged under the attachments to distribute the load.

An interesting method of supporting the tanks is that used in the Breda 32 low-wing monoplane. These tanks, which are made of brass, are carried in the leading edge of the main plane, outside the port and starboard engines. They are tied back to the single spar of the wing (which is described on p. 148) by straps passing right round the tank and anchored to the top and bottom booms. The straps are located on the tank shell by small angles at wide intervals, and can be tightened up by means of strainers. It will be seen that these supports lie well to the ends of the tanks between a baffle and the tank end.

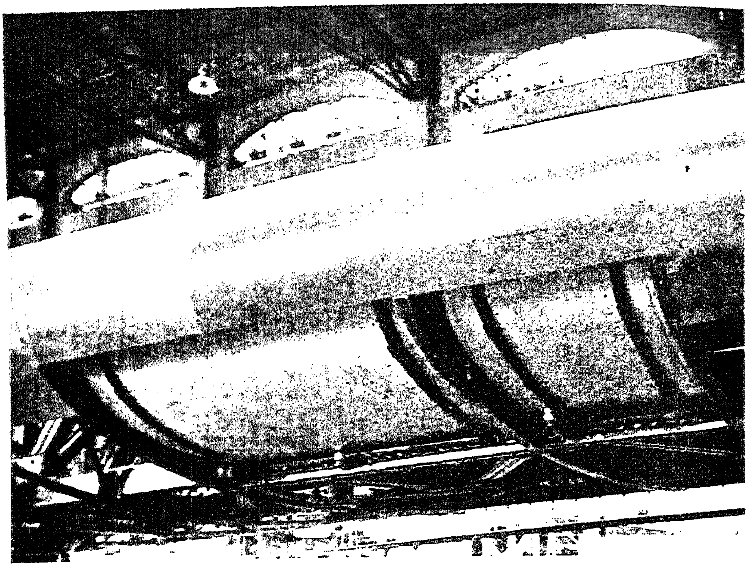


FIG. 393. BREDA 32—PETROL TANK MOUNTING

(*By courtesy of Società Italiana Ernesto Breda*)

The gauge fitting depends entirely on the kind of gauge used, whether it be a single boiler glass with cork float, or one of the proprietary types with a distant reading dial.

The design of oil and water tanks is in general the same as that of a petrol tank. Where cooling is required in the tank, adequate baffling must be provided to prevent the oil passing in a straight line from inlet to outlet, leaving the remainder of the contents untouched. The inlet may be arranged to cause the stream of hot oil to impinge on the cool outer surface, so that it is well spread.

Weights of tinned steel tanks are given in Fig. 394.[1]

Aluminium Tanks. The use of aluminium for tanks appeals strongly to the designer who has always to search for more lightness. Though

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[1] Reproduced by permission from the *Handbook of Aeronautics.*

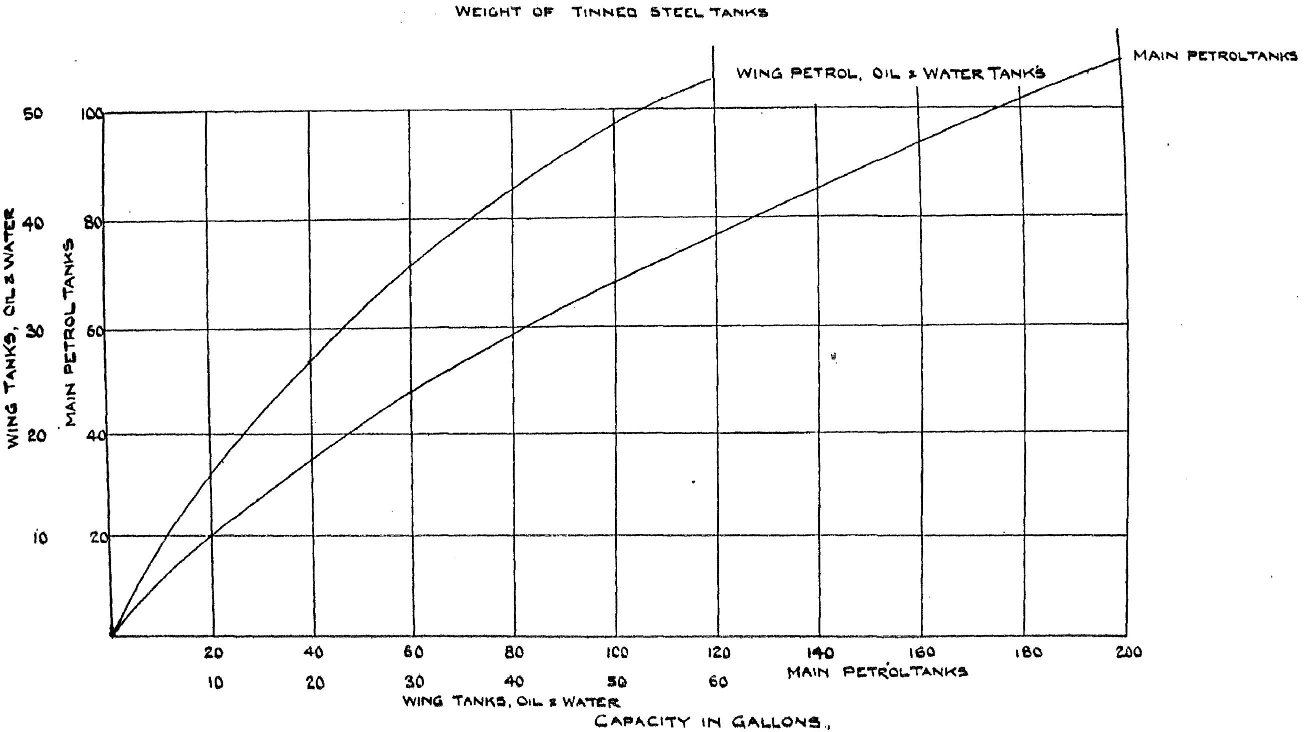
WEIGHT OF TINNED STEEL TANKS
WING PETROL, OIL & WATER TANKS
MAIN PETROLTANKS
WING TANKS, OIL & WATER
MAIN PETROL TANKS
50
40
30
20
10
100
80
60
40
20
20
40
60
80
100
120
140
160
180
200
MAIN PETROLTANKS
10
20
30
40
50
60
WING TANKS, OIL & WATER
CAPACITY IN GALLONS.

FIG. 394

oo weak a material for structural purposes, the small loads which a ank carries allow of its use. And a further strong argument in its avour is its property of welding easily, which ensures petrol-tight ints.

Yet aluminium is not without its difficulties, which must be understood before success is achieved.

Full advantage of its low specific gravity cannot be taken on account

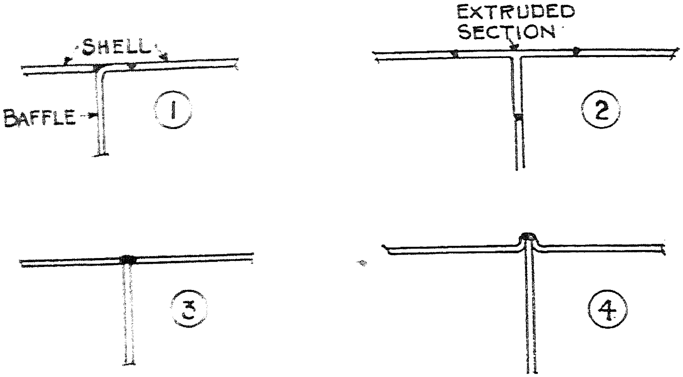

FIG. 395

of its softness. It is therefore necessary to increase the thickness to about twice what it would be in the corresponding tinned steel tank. Further, the surface must be divided into smaller panels, supported round their edges by baffle plates or bulkheads which separate the interior into compartments and prevent a large momentum being developed when the petrol swills from side to side.

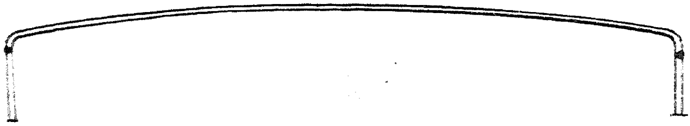

FIG. 396

The outside shell should never be less than 20 s.w.g. in thickness, and in large flat-sided tanks as much as 16 s.w.g. may be required. Baffle plates and bulkheads of 20 s.w.g. to 18 s.w.g. are satisfactory.

The tank should first be tack-welded together, the tacks being closely spaced.

The rapid expansion and contraction of the material during the welding process, combined with its softness, lead to buckling and distortion at all the joints. This trouble is particularly apparent when a too hot welding flame is used or when the work is done too slowly. To correct this buckling and at the same time to close up the texture of the weld, it is usual to hammer the joints wherever possible. The hammering is done on the outside against a backing-piece of wood held up against the inside by the operator.

Distortion may be restricted by correct design. It is good practice to arrange the joints in the shell at baffle positions. Typical joints are shown in Fig. 395. In a cylindrical tank it is frequently the practice to bell the end pieces and flange their edges, making a butt weld with the main shell (see Fig. 396). The flange should be small so that the joint gets the support of the end. Any panels which may have a tendency to buckle can be stiffened by swages, run in with a jinny before assembly.

Since the aluminium cannot be soldered satisfactorily, fittings such as pipe unions, filler necks, etc., must be welded in, and of such material as will form a weld with aluminium. At the same time it must be sufficiently tough to carry a thread. Aluminium silicon alloy to Specification L33 is a good material for the purpose. The flange on the fitting should be wide and run down at its edge to the same thickness as the shell. This ensures a gradual change of section and prevents the thread being distorted by the flame and heat.

The mounting of the tanks in the aircraft must be carefully carried out. The material is too soft to allow four-point support to be used, and any attempt to carry a tank rigidly will inevitably cause trouble. The weight must be taken on slings or braces which will distribute the load over as large a surface as possible. The slings, which may be of wide steel strip, should pass completely round the tank at sections where baffles occur, and it is usual to fit strainers in order that the slings may be drawn tight. The baffle flange should be at least as wide as the sling, and may conveniently be made of an extruded T-section as shown in Fig. 395 (2). Felt should be inserted between the sling and the tank surface. A further precaution against shock loads is the fitting of rubber buffers where the slings themselves are attached to the tank support girders or spars.

On completion, a tank must be thoroughly washed out with hot water to remove all traces of the welding flux, which, if left, would quickly cause corrosion.

The testing must be carefully carried out. A whiting of chalk and methylated spirit should be painted over all seams and allowed to dry. An inch or so of paraffin should then be put in the tank, and with all openings sealed an air pressure of 1½ lb. per square inch created with a pump or air bottle. If the tank is then turned over and about so that the paraffin can penetrate all the joints and welds, the smallest leak will show itself by a spreading stain on the chalk.

A variation from the welded aluminium tank is found in the Curtiss *Hawk* 75. The tanks for this aircraft had a riveted internal structure to which the shell was riveted. But the seams in the shell were welded as shown in Fig. 397.

The sump and outlet appears in the lower left-hand corner of the upper photograph. If this is compared with the illustration of the internal structure it will be seen that this corner of the tank is much more severely baffled than the others. Fuel can only enter it through the clipped corners of the baffles or, when the tank is full, through the flap valves near the top. Such a precaution against swilling is probably necessary in a flat tank of this sort, especially when mounted in a high-speed aircraft capable of rapid accelerations. Without it the sump might occasionally become exposed even when the tank was by no means empty, thus allowing air to enter the pipe lines.

The Fokker Aircraft Corporation of America claimed[1] a weight of

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[1] *Aviation*, October, 1930.

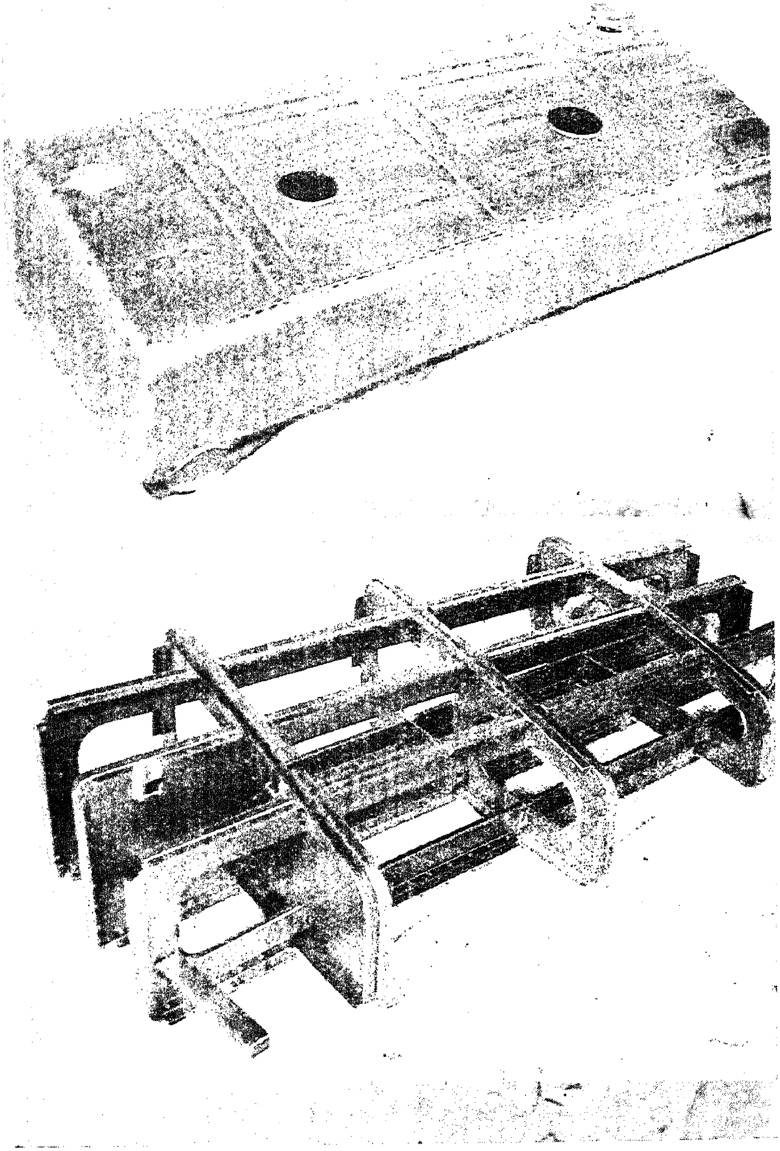

Fig. 397. Curtiss "Hawk 75" Tank Construction
(By courtesy of Curtiss-Wright Corporation)

0·45 to 0·55 lb. per gallon capacity for welded aluminium tanks. Dornier shows[1] a weight of 0·7 lb. per gallon with a tank of 11 gallons capacity, reducing to 0·36 lb. per gallon when the capacity is increased to 3,560 gallons. These figures, which are in general agreement, are from serviceable machines.

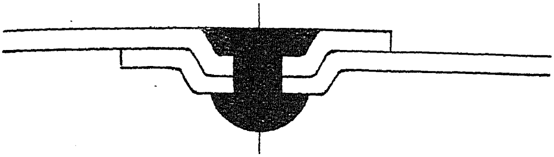

FIG. 398

Duralumin Tanks. Though duralumin is almost as light as aluminium and much stronger, it is more difficult to work and cannot be either sweated or welded satisfactorily. Other means of making the joints petrol-tight must, therefore, be found. A possible method is in the use of "De Bergue" riveting (Fig. 398) with some petrol-resisting jointing inserted between the sheets. Each rivet is put into a cupped conical depression pressed in the seam.

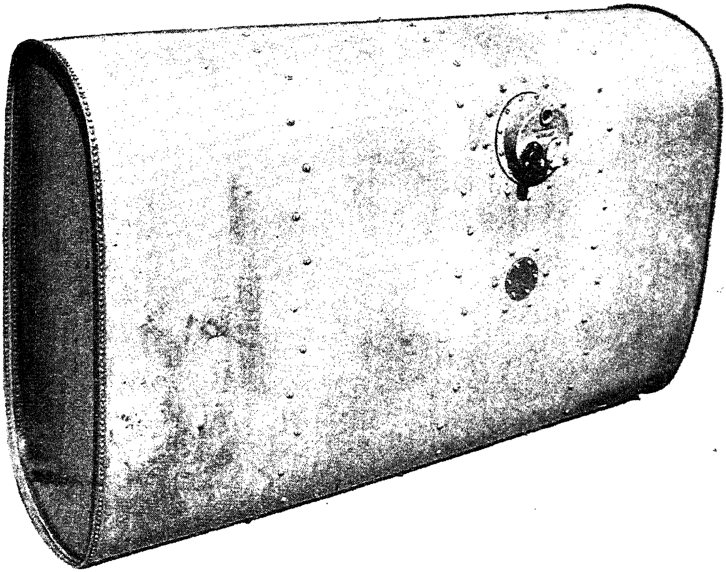

FIG. 399. GLENN L. MARTIN—RIVETED DURALUMIN TANK, 150 U.S. GALLONS

(*By courtesy of the Glenn L. Martin Co.*)

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[1] *Journal R.Ae.S.*, December, 1928.

In the U.S.A. duralumin tanks have been developed by the Glenn L. Martin Company (see Fig. 399) and the Curtiss-Wright Corporation. In the Glenn L. Martin tank the joint between the tank shell and end is covered with a U-piece with very closely-spaced duralumin rivets. Where rivets are used to fasten baffles in position, a cupped washer is inserted under the rivet head on the outside to give petrol tightness. The sump, which is clearly shown, is an aluminium alloy casting attached with closely-spaced screws which go through to an internal reinforcement. This type of tank has been thoroughly tested on a tank vibration machine before being released for production.

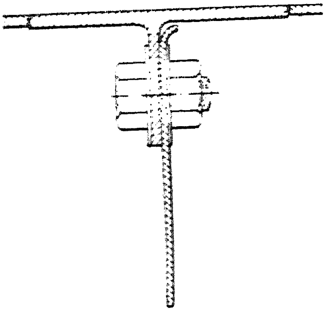

FIG. 400

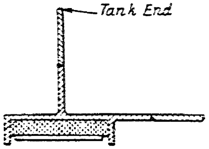

FIG. 401

"Elektron" Tanks. Fuel and oil tanks of magnesium alloy ("Elektron") are now being used successfully in large numbers of military and civil aircraft. The production and maintenance difficulties originally met with have now been eliminated by the use of suitable materials and technique.

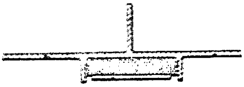

FIG. 402

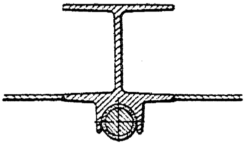

FIG. 403

The most widely used alloy is A.M. 503, which is produced under the following British Air Ministry specifications—

Sheet	D.T.D.118
Extrusions	D.T.D.142
Castings	D.T.D.140 A.

This material welds easily and has an ultimate tensile strength of 12–15 tons per square inch. Its proof stress is 6–8 tons per square inch.

The principal advantage of "Elektron" is its high strength in relation to its weight, the specific gravity being 1·83. It is thus possible, without serious loss of weight, to use a substantial thickness and to allow larger unsupported panels than with aluminium alloy or tinned steel. Because of its stiffness, the elektron tank requires few baffles.

The usual shell thickness is 18 s.w.g. (0·048 in.) and this is satisfactory for tanks up to 400 gallons capacity, if sufficient stiffness is provided by the shape of the tanks or by extruded sections welded into the skin. Flat panels up to 14 in. square in 18 s.w.g. may be used. If baffles are fitted they may be of 20 s.w.g. (0·036 in.).

In making up the tank it is necessary to allow for the effects of distortion due to welding. Thus if a baffle is first welded to the flange of a T-section shell stiffener the resulting bulkhead is too rigid for the subsequent welding of the skin. This should first be welded to the stiffener and the baffle attached afterwards. A satisfactory method is to attach the baffle by bolts as shown in Fig. 400.

A typical tank end, combined with strap suspension, is illustrated in Fig. 401, while a strap suspension at any other point along the length of the tank may be as shown in Fig. 402. If the suspension is by means of flexible steel cable, with a P.R. rubber hose covering, it may be as in Fig. 403. In these examples special extruded sections to specification D.T.D.142 are welded to the tank shell of D.T.D.118.

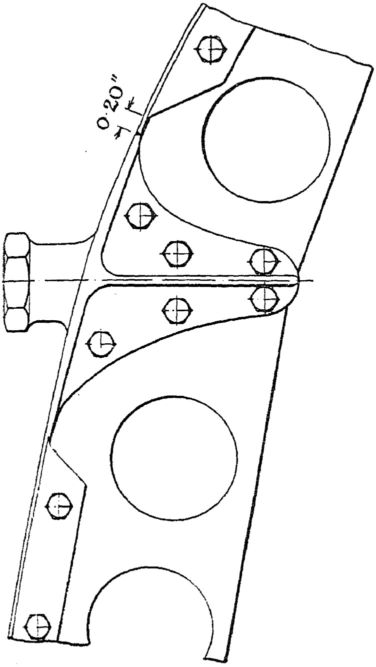

Fig. 404

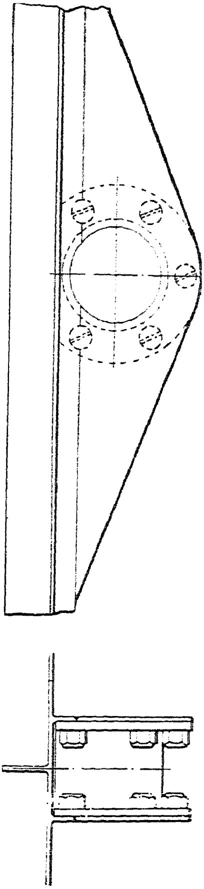

Fig. 405

Rigid suspension may be used if the loads are well distributed between the shell and the internal stiffeners. Such mountings may be necessary if leading edge or profile tanks are used, where the presence of an external strap would be aerodynamically undesirable. One typical example is shown in Fig. 404. A casting of D.T.D.140 A is used and this is welded to the skin and bolted to the internal stiffener. The minimum thickness for castings should be 0·125 to 0·15 in., and the skin of the casting should be removed up to 0·25 in. from the welding edge. It will be seen that the web of the T-section stiffener is cut back 0·20 in. from the end of the flange so as not to make too stiff a point near the welding.

Another example of rigid suspension is given in Fig. 405. The webs of the extruded section are extended locally by welding on additional lugs of the same thickness. After hammering, the welded seam may be nearly as strong as the original plate.

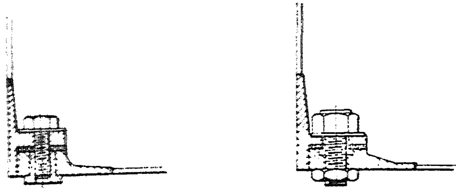

Fig. 406

Tank fittings may be attached by welding them directly to the shell, or by bolting them to adaptors which are welded in (Fig. 406). The bolts may be of steel or aluminium alloy provided that they are not located in a pocket in the tank bottom where water might collect. They should be assembled with an insulating paste having, for example, a barium chromate base.

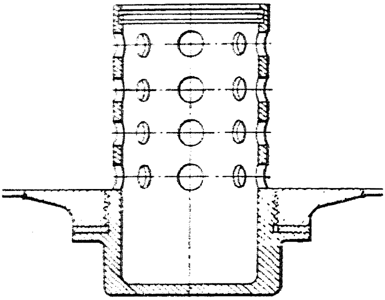

Fig. 407

Water is always present in petrol and this may cause corrosion if the fuel is a leaded one. It is therefore essential to use some inhibitor. The usual method is to carry a small bag of chromate salts in each elektron tank. These dissolve slowly in the water and make it innocuous. One ounce of the salts to each 100 gallons capacity is the usual measure and it must be renewed annually. The bag is carried in a cage of M.G.7 alloy, screwed into an adaptor as shown in Fig. 408 and fitted at the lowest point of the tank, water being heavier than the fuel and therefore gravitating to the bottom. Pockets in which water might collect must be avoided and therefore small holes should be drilled in the webs of any stiffeners across the tank bottom.

In order to reduce the cost and to save weight, tank fittings may be

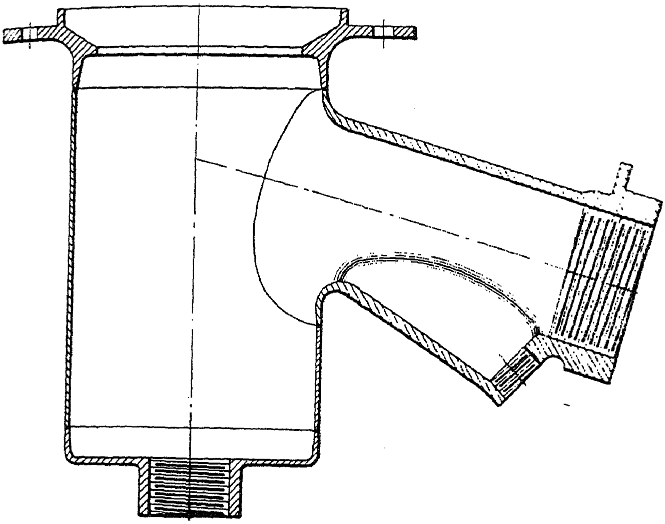

Fig. 408

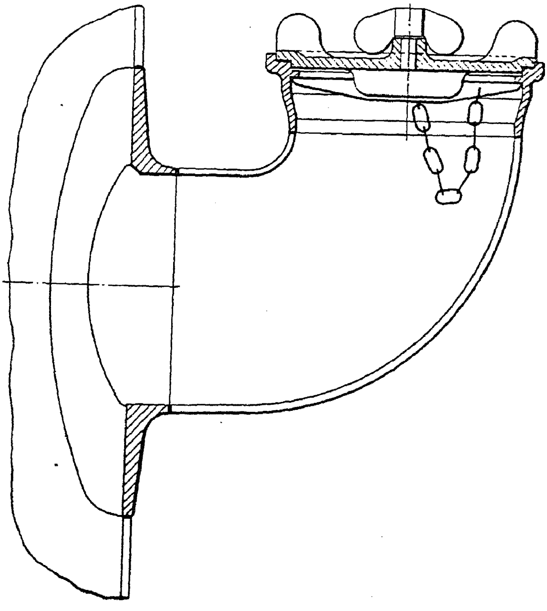

Fig. 409

made up by a combination of castings, machined fittings, and plate (see Figs. 408 and 409). This allows one to go below the minimum thickness of 0·125 in. which is necessary in a casting and to use 18 s.w.g. plate and machined parts of similar thickness.

Star plates such as are used to stiffen the skin of tinned steel tanks should be avoided. The number of changes in the direction of the weld would lead to trouble and cause flux inclusions, giving points of weakness and corrosion. If stiffening plates are necessary they should be circular and of thicker gauge than the tank shell. As in all the other examples given above butt welding must be used to attach them.

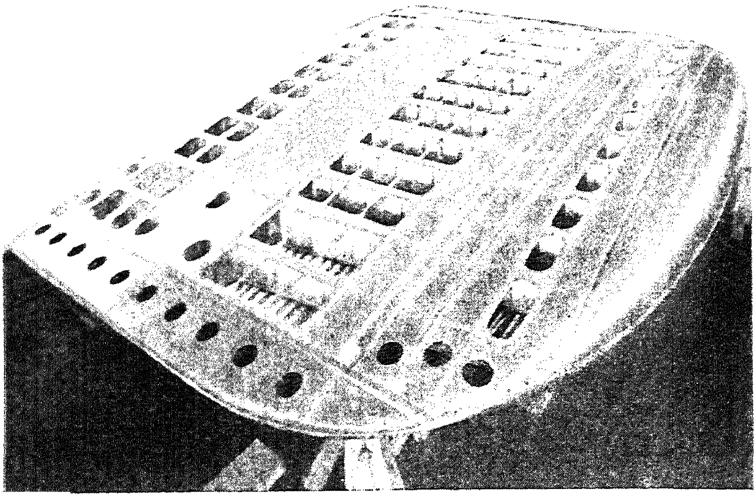

FIG. 410. GLENN L. MARTIN "CHINA CLIPPER," SEA WING AND FUEL TANK

(By courtesy of the Glenn L. Martin Co.)

On completion the tank should be given the standard cold acid chromate dip and painted externally with two or three coats of an approved lacquer (see page 392).

Integral Fuel Tanks. The tanks described above have developed with the conventional lightly loaded fabric-covered structure. The growth of the stressed skin structure which is relatively heavily loaded and of robust gauge has brought attention to the possibility of dispensing with independent tanks and of carrying the fuel in special compartments of the structure itself. Precedent for this is found in naval architecture.

Note. The illustrations and information in this section are given by courtesy of *Flight* and Messrs. F. A. Hughes & Co., Ltd., Abbey House, Baker Street, London, N.W.1.

the tanks of a ship being fuel-tight compartments of the primary structure.

In England this principle was used as long ago as 1926 when the midship portion of the starboard float of the Supermarine S.5 Schneider Trophy seaplane was used as a tank. The use of a single tubular spar in the wing as a fuel tank has been mentioned on pages 78 and 141, in descriptions of the Blackburn-Duncanson and the Hamburger wings.

In America integral fuel tanks have been used by Seversky, Glenn L. Martin, Curtiss-Wright, Lockheed, The Consolidated Aircraft Company, and others.[1] The Martin *China Clipper* had tanks built into the hull, between the planing bottom and the cabin floor. Fuel was also carried in the lateral stabilizers or "sea wings" (see Fig. 410).

Because of the very high loads which may be imposed on the sea wing, it must be robust and it may be made relatively inflexible. There is therefore less chance of leaks developing. In this example it will be seen that a very solid internal structure is provided and that the fuel is not free to swill fore and aft. Its level will, of course, be maintained through the gaps where the inner corrugations of lower surface cross the spars, but these are not sufficiently large to allow violent movement.

The integral fuel tank of this sort shows a great saving in weight and while no rule can be laid down it is suggested that a tankage allowance of as little as 0·1 lb. per gallon on top of the structure weight may be sufficient. In military aircraft, however, the growing popularity of the integral tank clashes with the necessity for making the tank bullet-proof. This is done by enclosing it within a pure rubber casing, a process which may be easily applied to the tubular spar tank but is difficult to imagine in other cases.

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[1] See *Journal of the Aeronautical Sciences,* Vol. 4, No. 3, January, 1937, "Integral Fuel Tanks," by Horace J. Alter.

CHAPTER VII

WORKSHOP PROCESSES AND DETAIL DESIGN

Most of the workshop processes used in an aircraft factory are those common to all engineering practice. There are, however, many which have been evolved for aircraft work, or which, though used elsewhere, have developed a special technique when applied to this class of work. Some of these, such as welding and hull construction, which dictate the details of design, have already been described in conjunction with the design.

The Manufacture of Strip Spars, Ribs, etc.

The general design of thin strip sections has already been dealt with in Chapter III, and many examples were illustrated. The principal feature of strip structures is that the material, being thin, must be corrugated to give it stability. The technique of producing corrugated sections is one which the aircraft industry has had to develop itself, although the elements of it are known and applied in other industries. Much experimental work is still being done and many methods have been tried. Amongst these were folding and pressing, but not being applicable to long lengths and the more complicated shapes, they have been largely superseded.

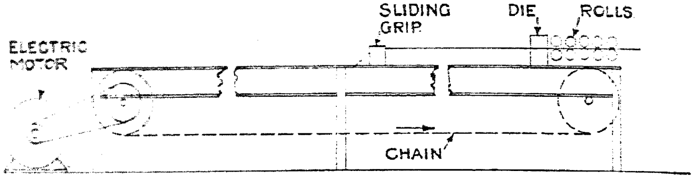

Fig. 411

The method now used almost universally is drawing through dies or rolls. The details vary considerably from factory to factory, but the principle is the same.

A draw bench (Fig. 411) consists of two long parallel rails or channels, back to back, some 6 in. or 12 in. apart. At each end between the girders is a large sprocket, round which passes an endless chain so arranged that the upper length of chain is level with the top face of the rails.

The sprocket at the left-hand end is driven by an electric motor, thus causing the chain to travel in an anti-clockwise direction, as seen in the diagram. At the right-hand end is arranged a battery of forming rollers and a die through which the strip passes. The end of the strip is held in a grip which slides on the rails hooked into the chain. When the full length of strip has been pulled through, the motor is stopped, the grip de-clutched from the chain, and the formed strip removed. Fig. 412 shows the type of draw bench evolved by the Bristol Aeroplane Co., Ltd., for strip steel work. This draw bench has been used for pulling the sections together in assembling spars and tubes with the interlocking joint, peculiar to Bristol practice (see Fig. 9/B). For the actual fabrication of the corrugated sections themselves, a set of rolls is used. The advantages of rolls over dies are firstly that the speed is greater, and secondly, that grit, if drawn through the die with the strip is very liable to scratch the

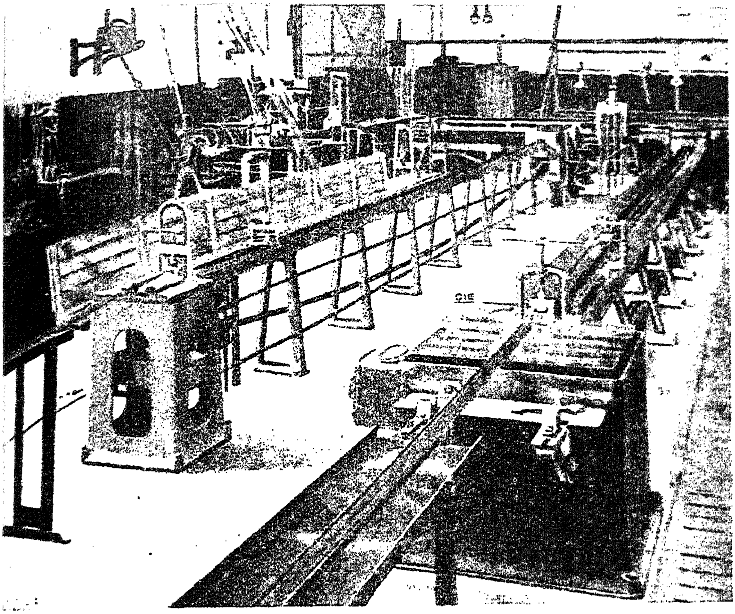

FIG. 412. STRIP DRAW BENCHES AT THE BRISTOL WORKS
(By courtesy of the Bristol Aeroplane Co., Ltd.)

surface. A rolling speed of 30 ft. per minute or up to 1,500 ft. per hour is regularly attained.

Lengths up to 70 ft. were handled by Boulton & Paul in the fabrication of R101, and draw benches capable of handling strip from three-quarters of an inch to a foot in width are in daily use. The materials

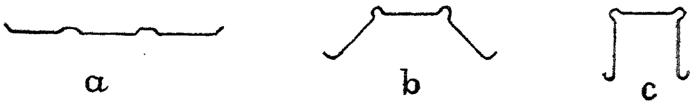

FIG. 413

put through this process vary from high-tensile steel 0·005 in. thick to duralumin 0·10 in. thick.

The whole problem of draw bench work lies in the design of the rollers and dies, which must be suitable for the particular material to be formed. Simple sections in duralumin may be made through a single die. In the more complicated sections the final shape can only be attained by the use of multiple dies or rollers, each of which adds to the curves or bends required. Fig. 413 illustrates three stages in the formation of a beaded edge channel. The shapes *a* and *b* may be produced either through dies or rollers, preferably the latter. It will be seen that the small kinks are put in first, and serve to locate the strip, preventing it from wandering sideways. The rollers for *b* are shown in Fig. 414. The strip passes through at a constant speed, but all parts of the roller at different distances from the axis cannot be travelling at the same speed. In order that the worst "slip" between strip and roller shall be as small as possible, the split between the rollers is kept at the median line of the section. The rollers are usually made in case-hardened mild steel, when the expected production is not large. For large quantity work the extra expense of making them in a hardened nickel steel is allowable.

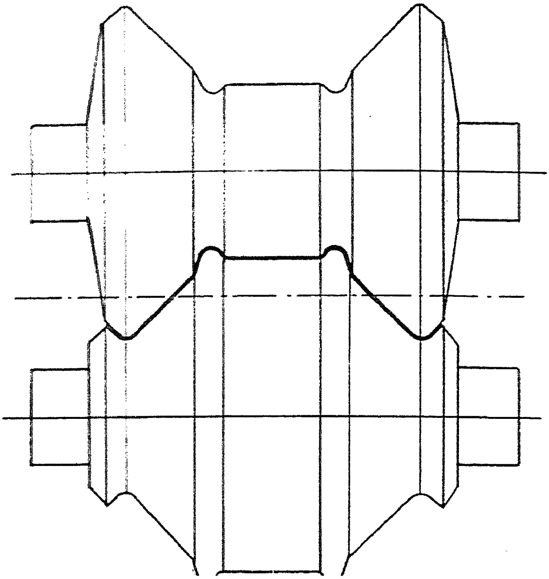

FIG. 414

The rollers run freely as the strip is drawn through them, the upper being adjustable by a hand screw to regulate the pressure. In the Armstrong-Whitworth draw benches the lower rollers are fitted with a spur gear for use when the strip is first fed into them. They are coupled together through these gears by means of a rack. One of the rolls is turned with a lever, and all move at a uniform speed until sufficient strip has been fed through to be gripped by the slide. The lever and rack are then removed, leaving the rollers free to rotate. At the Bristol works the strip is not pulled through the rolls. The rolls themselves are driven and carry the strip through by their rotation. Although this has the possible disadvantage that the strip may be in compression between each pair of rolls, it allows greater lengths to be handled. The length is not limited by the length of the draw bench.

The final shape in the example given is obviously not easy to produce between rollers owing to the reverse bends. It must, therefore, pass through a die shaped to *C*. This may be fairly long and of cast iron with a good lead into the final section where the strip leaves the die. As with rollers, a harder material may be used when large production and the consequent wear are expected. Or the case may be met by bolting on a hard steel face at the outer final end of the die (Fig. 415). Some closed sections, however, may be completely made by rolling. It is necessary to have the closing rolls about vertical, instead of horizontal, axes. The number of rollers and dies, and the shapes of the first and intermediate sections, depend on the material of the strip and the amount of shaping. As many as six sets of rollers may be necessary. Experience of the many variables involved and constant experiment are the only means of attaining success. When a correct set has been found for any particular section which is likely to be used repeatedly, they should be made up in the form of a permanent battery which can be fitted to and removed from the draw bench as a single unit.

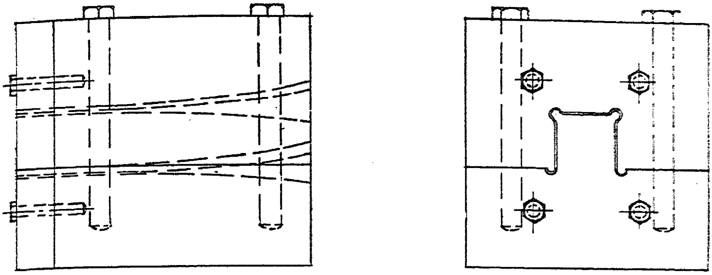

FIG. 415

An example from the Dornier factory of a complicated section produced entirely by rolls is shown in Fig. 416. It will be seen that a battery of eight rolls is needed to give the final shape. The work is first done on the centre of the strip and then each successive shaping out to the edges is added. The sides are finally closed up by two oblique rolls.

The Dornier rolls are capable of handling strip from 0·015 in. to 0·10 in. in thickness at speeds from 16 to 80 ft./min. The drawing force is from 3 to 10 tons depending on the thickness and the section being drawn. Duralumin is usually rolled by Dornier in its final heat-treated condition.

The rolling of the curved bracing members in a Vickers geodetic structure (see pages 96 and 100) would seem to be extremely difficult. It is done on a special type of rolling mill, patented by Vickers, and using five to seven pairs of rolls, which give the section its predetermined curvature in the one operation (see Fig. 417).

In this example, unlike the Dornier, the side flanges are turned up first, the reverse bends being given by vertical rolls. These are so placed, and moved by cams, that they begin to give the member its curvature. The centre corrugation is added by the last set of rolls which also completes the curvature. The control of the cams is such that the radius of curvature can be varied along the section as it passes through. In the Vickers *Wellington* the geodesics were all of the same section but the thickness ranged from 12 s.w.g. to 22 s.w.g. There were over 1,650 separate members in each aircraft and the material was duralumin.

In drawing duralumin strip, the material is first cut to the correct width. The raw coil is mounted on a drum, the free end being fed through rollers with disc cutters at each end. The width between the cutters must be adjustable within fine limits, and the feed must be exactly at right angles to the cutter axis. As it leaves the cutters the strip is run on to a second drum. It is then fully heat-treated in the coil at 490° C., and the drawing must be done within the two hours before age hardening becomes apparent. After washing and before drawing, the whole coil should be dipped in melted beeswax and tallow, which act as a lubricant. The section is then drawn, cut to length, cleaned, and anodically treated.

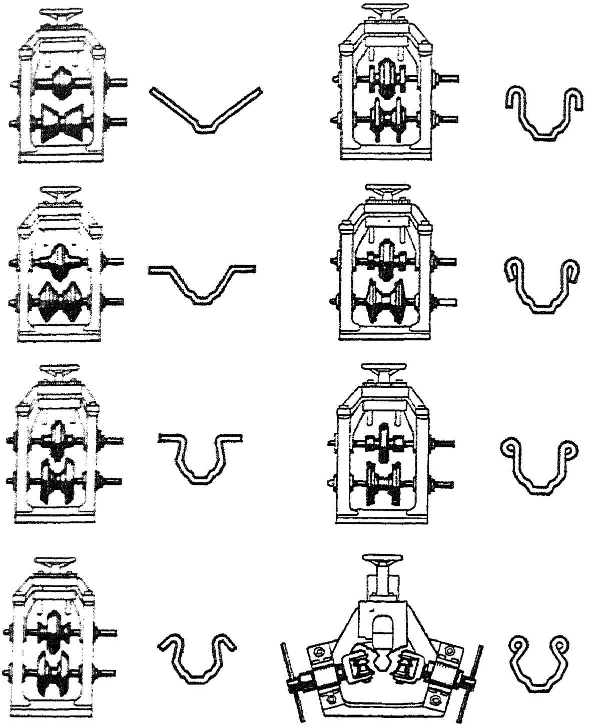

FIG. 416. DORNIER DRAW BENCH ROLLS

(By courtesy of "Aircraft Production")

It is inadvisable to design sections with tightly-closed beadings in duralumin. Beeswax and dirt collected in inaccessible corners will cause trouble in the anodic bath and thin material may be almost eaten away, or at least severely pitted, at these points. Absolute cleanliness is essential, and the section must be such as to make it possible.

In the drawing and rolling of strip steel sections there are two schools of thought over the question of heat treatment. In some factories, notably Bristol and Hawker, the strip is received slit to width and heat treated to the final strength. It is rolled in this hard condition. The alternative method, followed by Armstrong-Whitworth and Boulton & Paul is to buy the strip in the annealed condition, to roll it in this state and to heat treat to full strength afterwards. Hard rolling reduces the number of operations to be carried out in the aircraft factory, and is not difficult to do. On the other hand, it is claimed for soft rolling that the wear and tear of rolls is less, that the difficulties of "spring-back" are eliminated, and that the heat treatment process is simple and exact if carried out by electrical methods.

In the Boulton & Paul plant the formed section in the annealed state is fed into an electric muffle furnace, through which it passes at a speed appropriate to the temperature required. It will be understood that such thin material quickly attains the tempering or hardening temperature. As the section passes out at the far end of the furnace, after being heated and "soaked" as it goes through, it is fed into a hollow cast-iron, water-cooled die, which maintains the shape whilst cooling it finally. It has, however, passed through the critical cooling range in the short air gap between the furnace and die. The steel used is, appropriately, an air-hardening one.

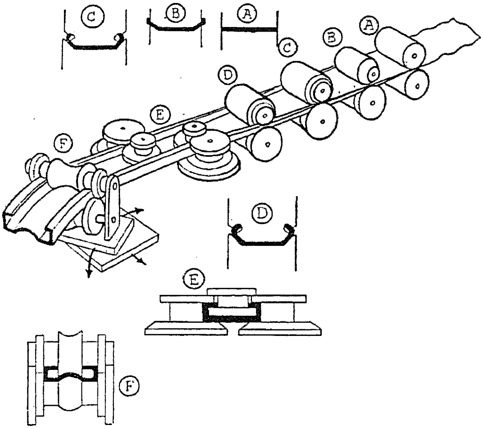

FIG. 417. VICKERS DRAW BENCH ROLLS FOR CURVED MEMBERS

(*By courtesy of "The Aeroplane"*)

The Armstrong-Whitworth method of hardening and tempering is different in that the formed strip in the soft state is made a resistance in an electrical circuit. It is drawn taut in a vertical brick-lined chamber, the lower end just passing through a die which closes the bottom of the chamber. The current is gradually turned on until the required amount is passing and the correct temperature reached. About fifteen seconds are taken to attain a temperature of 820° C. to 850° C. The current is left on for 30 sec. and then decreased so that the temperature drops to 700° C. The strip is then passed down through the die, which removes the scale, into the quenching pit below.

In the annealed state, when drawn, the steel has a tensile strength of 40 to 45 tons per square inch. It is hardened to 110 tons per square inch and then tempered back to 80 to 90 tons per square inch, the material being nickel-chrome steel to D.T.D. Specification 54A[1]. The tempering process is in principle similar to the hardening. For this, the strip is clamped horizontally under tension, and the temperature raised to 420° C. This is maintained for 90 sec., after which the strip cools off in the air.

Without jigs the assembly of the various corrugated strips into the final spar, rib or strut would be difficult. The parts must be held firmly in their correct position relative to each other while the drilling and riveting are done. Not until the work is completely fastened together may it be safely released, if accurate and consistent dimensions are to be worked to.

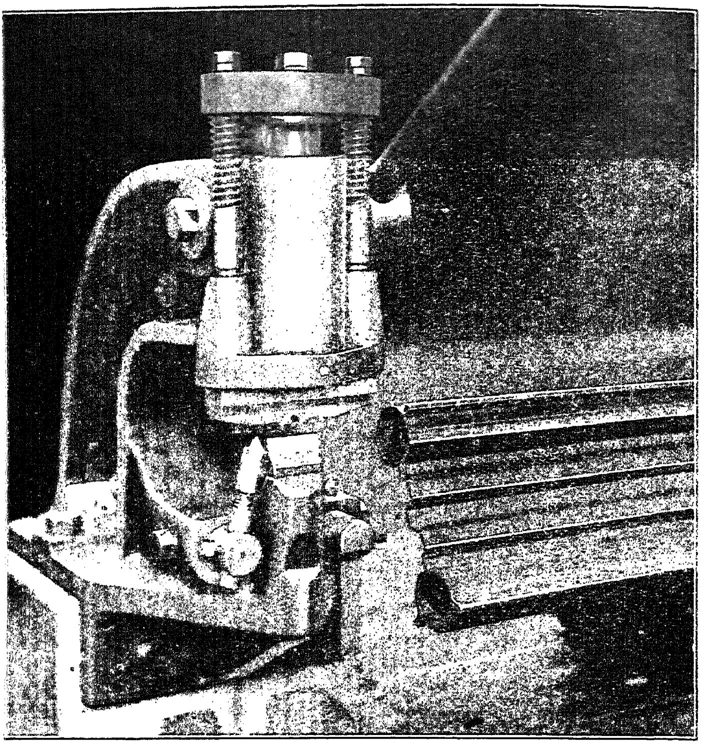

FIG. 418. ARMSTRONG-WHITWORTH SPAR FLANGE PUNCHING MACHINE

(By courtesy of "Machinery")

The Armstrong-Whitworth spar (Fig. 11, B) would appear as troublesome as any to put together owing to the number of pieces involved. By thorough jigging, the cost of which is covered by their large output, the work is reduced to almost mechanical operations. The strips, having been drawn to shape, heat treated and tempered, are cut to their correct length. The first portions to be assembled are the inner segments of the booms to the web. The jig for this consists of two tubes acting as dummy

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[1] Now known as B.S.I. Specification S.88.

booms the correct distance apart. They are complete with a flange to represent the outer segment of the boom. The inner segments are held in their correct positions on the dummies, and the web plate placed between them and gripped. Widely spaced holes are punched and rivets put in to hold the inner segments and web together. The punching and riveting throughout the whole length is completed. The work is then removed from this jig and any tubular stiffening in the booms located in position. The spar is ready to have the outer boom segments added and the corner jointing strips pulled over the small flanges. For this the spar is held vertically in fixtures along a bench, at one end of which is a hand windlass. A cable passes round the windlass, and at its free end has a clamp which grips the jointing strip. Once the jointing has been fed on to the flange, it is pulled down the spar by turning the windlass, small clips being put over it at intervals to hold it until riveted.

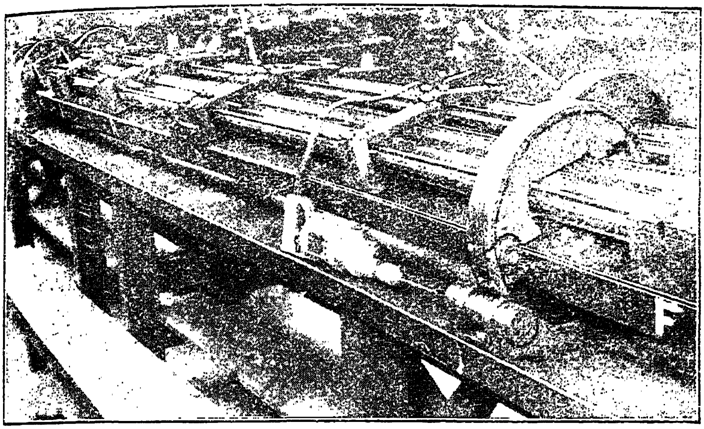

FIG. 419. ARMSTRONG-WHITWORTH SPAR DRILLING JIG
(*By courtesy of "Machinery"*)

The punching and riveting are hand done (see Fig. 418). The final operation is the drilling for fittings. The jig is shown in Fig. 419. The spar, now completely riveted up, with all internal stiffening added, is clamped to a long steel channel. This is supported at three points by circular rims which run in flanged rollers on the bench. The whole job can thus be rotated to any angle at the wish of the operator. Bushed drilling jigs are located at fixed positions on the channel base, and the drill has merely to be put through these, there being no measuring on the job. With jigs of this kind it should be possible to assemble a whole spar without once using a rule.

The rib construction is similarly reduced to a series of mechanical unskilled operations. The rib, which is shown in Fig. 49, is built up from lipped channel booms with square section cross bracings. The bracings are cut to length and their end holes drilled in an adjustable jig. The end hole, having been drilled, is used to locate the bracing on a peg, round which it is rotated against a small grinding wheel which radiuses the end.

The booms are bent to contour on a former which carries a travelling guide on rollers (Fig. 420). As the operator pushes the guide along, he puts retaining C slips round both boom and former. Any small wrinkles which tend to appear in the boom flanges on bending are pressed out by the travelling guide as it passes. The boom, now bent to shape, is clipped to a vertical jig (Fig. 421) by clamps which also hold drilling bushes, and the rivet holes put in.

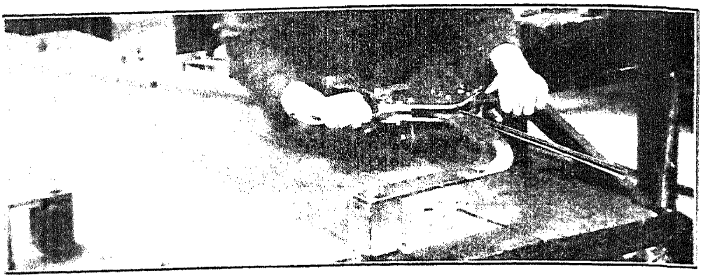

FIG. 420. ARMSTRONG-WHITWORTH RIB BOOM BENDING TOOL

(By courtesy of "Flight")

The rib is assembled on a rotating wooden jig (Fig. 422). The holes which already exist in both booms and cross bracings are matched up by a pointed peg and blank tubular rivets inserted. The ends of these are belled with the pincers as shown in the illustration. The rib is removed and the rivets finally closed down.

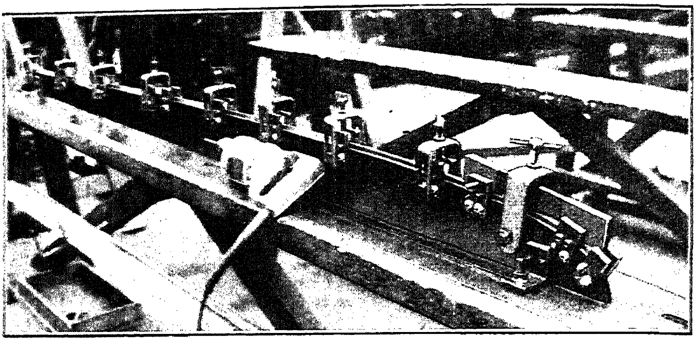

FIG. 421. ARMSTRONG-WHITWORTH RIB BOOM DRILLING JIG

(By courtesy of "Machinery")

In the process used by Lioré & Oliver in France the bracings are cut to length and the booms contoured, but no holes drilled at that stage. They are then assembled in a flat bench jig on rails, over which a lid closes. The lid is furnished with drilling bushes. After drilling, the lid is opened, rivets dropped into the holes where they hold the rib together sufficiently to allow it to be lifted out of the jig and transferred to a press, which closes the rivets. A particularly neat point in this system lies in the fact that the jig, being on rails, can be passed down the bench from one operator to the next. The first puts in the booms and braces, the second drills the holes, the third inserts the rivets and lifts out the rib, handing it to a fourth, who closes the rivets. It is claimed in this way that the average time with female labour is 30 min. per rib.

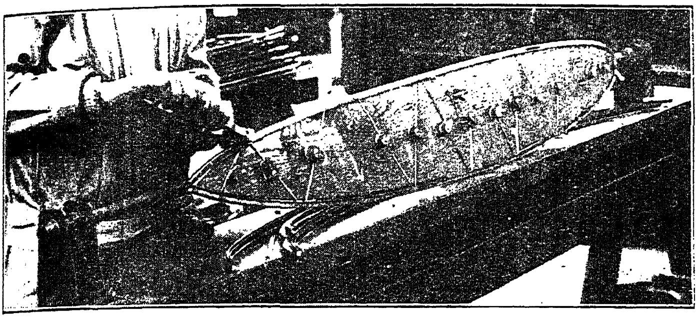

FIG. 422. ARMSTRONG-WHITWORTH RIB ASSEMBLY JIG

(By courtesy of "Flight")

THE EXTRUSION PROCESS

The extrusion process for forming sections in light alloys has made great progress in recent years and its development has been encouraged by the almost complete substitution of aluminium alloys for steel in the main wing and fuselage structures. The process is not one operated by the aircraft constructor who always buys his sections ready extruded from some specialist firm.[1]

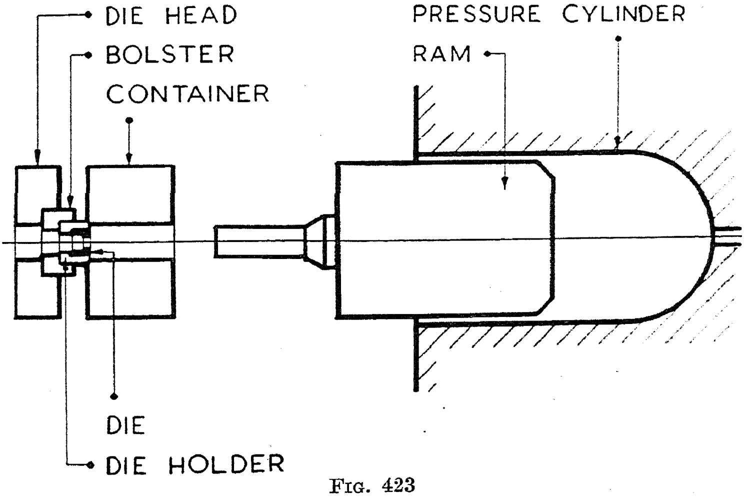

FIG. 423

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[1] The following description is taken from an article by R. Worsdale, of The Reynolds Tube Co. Ltd., in *Metallurgia*, February and March, 1939.

Extrusion is defined as "the forcing of metal heated to plastic state through dies by pressure." For extruding aluminium alloys an hydraulic press is usual. Such a press consists of a container which receives the pre-heated ingot, the die, a pressure cylinder and a ram (see Fig. 423).

The ingot is placed in the container which is closed at one end by the die and at the other by a pressure disc. The cylinder applies pressure to this disc through the ram and the metal is forced to flow through the die taking the contour to which the die is cut. It is not necessary here to go into further details of the hydraulic press, but there are several points in the process which should be understood by aircraft designers and draughtsmen, so that in asking for new sections they may know the limitations of the process and how to suit their design to it. In the die head is fixed a die plate, a holder and a bolster. The die plate is the most intricate part of the mechanism, and it must be cut very carefully if the process is to be successful.

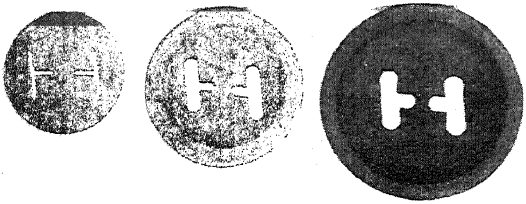


FIG. 424. EXTRUSION DIE, DIE HOLDER, AND BOLSTER
(By courtesy of "Metallurgia")

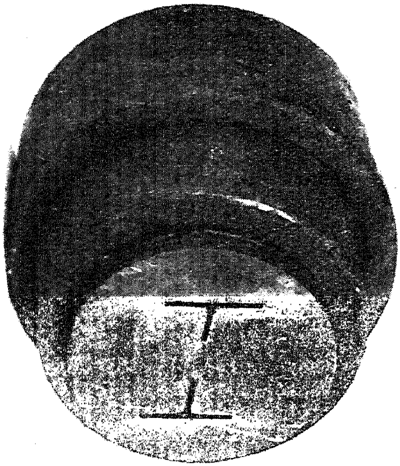


FIG. 425. EXTRUSION DIE ASSEMBLY
(By courtesy of "Metallurgia")

A templet is first made to the exact shape of the desired section with suitable allowances for contraction. The die is cut from this templet and is a machined disc of nickel-chrome-tungsten steel about 1¼ in. thick, the diameter being suitable to the size of the section and the press on which it is used. The die is hand-finished to extremely fine limits, and it is highly polished. A section is cut clear through the die and there is no "lead-in" when aluminium alloys are to be extruded. For magnesium alloys a slight radius is cut on the edge of the section. For this reason a die made for aluminium alloys can seldom be used for magnesium, and vice versa. The die itself is not strong enough to stand very high pressure and it is supported in a die holder with a special bolster (see Figs. 424 and 425).

The holder and bolster are of forged nickel-chrome-tungsten steel cut to the same contour as the die, but larger, to allow the extrusion to pass through without touching. These tools are carefully hardened and tempered and they fit very accurately into the mouth of the container so that no metal can escape during extrusion.

The ingots are heated to the particular temperature required, usually between 380° C. and 480° C. To prevent the metal flowing back over the stem of the ram during extrusion, a pressure disc is used. This fits the container with a small clearance and is inserted after the ingot and between that and the ram. Under pressure the metal flows through the die in an extremely interesting way.

Only that metal which is directly opposite to the die opening is forced through it. As the metal is under pressure and cannot expand outwards it must flow to the rear of the ingot and then down the centre. If the operation is not carried out carefully, there will be "coring" or "piping" in the finished section. This phenomenon, which cannot be entirely eliminated, controls, to some extent, the length of discarded ingot left behind in the container. The usual speed for average sections is 3 ft. per min. The metal is changed entirely from the cast to the wrought condition, and the high pressure used in the process gives extrusions a dense uniform structure, much more reliable than that of rolled bars where the outside of the bar received a lot of cold work whilst the centre was relatively unaffected. After the sections have been extruded, they are heat-treated, straightened, cut to length and tested.

It is difficult to define limits which the manufacturing process puts on the design of sections, but the technique is improving year by year, and sections are now being produced which would have been considered impossible until recently. At one end of the scale are T-sections 0·040 in. thick by 0·75 in. overall dimensions, weighing 1 oz. per ft., and at the other are sections 1 in. thick by 6½ in. overall depth weighing nearly 20 lb. per ft. Conventional sections such as tees, zeds, and simple channels do not present any great difficulty, but trouble is experienced in channels where the depth is greater than the width. The sections shown in Fig. 426 were difficult, in that the sides are of a different thickness from the base, and the ratio of depth to width is relatively big. In extruding such sections the whole of the pressure of the tongue of the die is taken across the top where the sides end. The greater the depth of this tongue the greater is the tendency of the die to break at that point.

For sections such as these, the die and its holder are made in one piece, or, alternatively, the holder and bolster are made in one. Where the channel is very deep and narrow it is extruded with the webs splayed out. and subsequently drawn parallel after extrusion. This considerably increases the cost, and it can only be done on sections which are of simple outline and reasonably constant thickness.

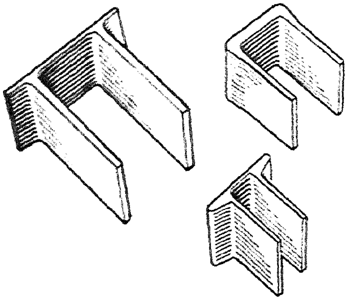


FIG. 426

There is a definite ratio between the minimum thickness and the largest overall dimension. The cross-sectional area of the section, particularly when it is complicated, has a distinct bearing on whether it can be extruded or not. Thus it is possible to produce a 1 in. T-section 0·04 in. thick but not one of 3 in. and that thickness. This is due to the fact that an ingot can only be reduced in area by a certain amount. For small sections it is usual to cut the die so that several may be extruded at once. With a larger section it would not be possible to produce it in a multi-hole die owing to its large overall dimension and the reduction in area from that of the ingot to that of the section would be too great for any press to handle. Definite rules cannot be laid down, and the practical experience of the extrusion manufacturers should be used in case of doubt.

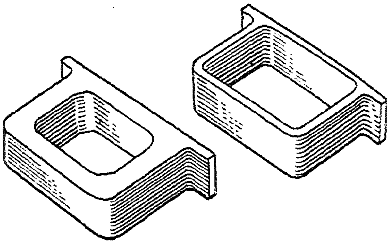


FIG. 427

Considerable trouble is found in producing certain extruded sections to very fine limits. It is sometimes possible to draw the sections to fine limits after extrusion, but this involves additional expense, and should only be asked for when absolutely essential. The factors which affect the tolerances are numerous, e.g. there is always a contraction of the metal after extrusion, and whilst this can be allowed for in the manufacture of the die, the use of this die on a different hydraulic press may produce slightly different dimensions. The straightening operation after heat-treatment may require special tools if the section is not conventional, and this again leads to additional expense, particularly if long lengths are required. It is possible to manufacture by the extrusion process sections and tubes of very irregular shape.

The hole, however, must be symmetrical about both axes of the section since the mandrel is located in the centre of the stem of the press and an even pressure must be inserted by the extrusion so as to maintain it centrally. The four walls of square or rectangular sections do not have to be of the same thickness provided that the pairs opposite to each other are the same.

Eccentricity is, therefore, to be avoided, and the tendency of the process is by its very nature to make symmetrical sections. A recent development of the technique of extrusion allows sections to be made having tapering wall thickness. That shown in Fig. 427 is an example showing the end sections which were cut from one extruded length.

The taper does not have to be gradual and straight from one end to the other; it could vary and parallel portions may be introduced. The section of the hole can also change throughout the length from round to rectangular, for example.

Solid taper sections are now being made as, for example, tee, angle, and zed sections in which the flanges taper in thickness along the entire length. This is a valuable property and saves a great deal of machining in the manufacture of spars for tapering wings. Many other savings become possible by the careful design of extruded sections, and much machining may be eliminated. A very ingenious example of this is shown in Fig. 428, which illustrates a spar joint from a Short Empire Boat. The spar flanges are large extruded T-sections, approximately 5 in. × 6 in. × 1 in. The bracing tubes are joined to the flanges by means of standard extruded blocks like that on the left of the illustration. These are made in long lengths, parted off and shaped. Many other examples of extrusions will be found in the chapters relating to main plane and fuselage construction.

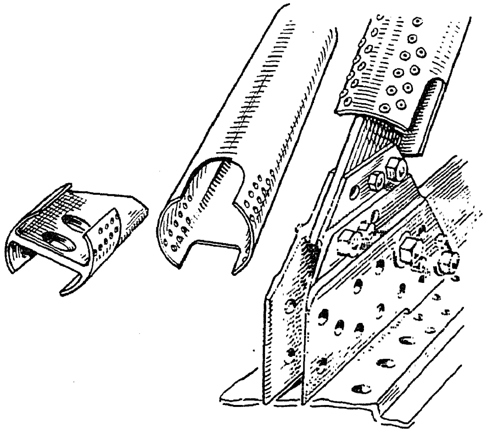


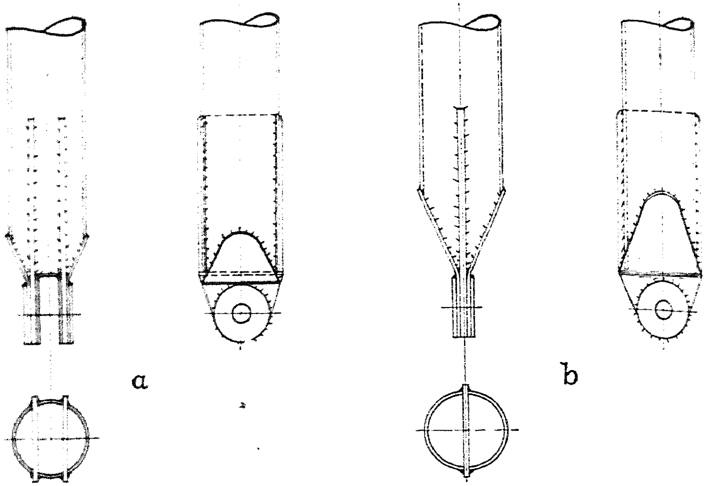
Fig. 428. Short "Empire Boat" Spar Joint, showing Use of Extrusions

Detail Fittings

Many examples of detail fittings have been illustrated and discussed in the preceding pages. Some have been of bent plate, others machined from bar, and yet others have been drop forgings. Castings have only been found in small unstressed parts, such as the blanks for tank caps. Cast metal is too unreliable in its texture for primary structure carrying big loads with small factors. Metallurgical improvements in certain aluminium and magnesium alloy castings are leading to their use for secondary structure. The inspection, which should include X-ray methods, must be rigid.

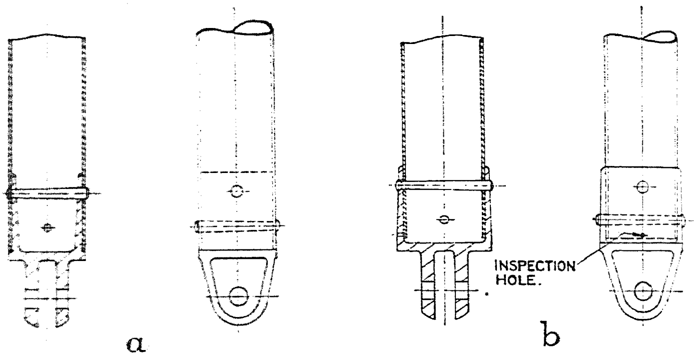
Fig. 429 illustrates tubular strut ends made of bent plate, welded, *a* and *b*, and end sockets machined from bar or from drop forged blanks are shown in Fig. 430, *a* and *b*. These will serve as examples for a comparison of the different methods.

The welded plate end, *a*, will be seen to consist of seven pieces, three



WELDED PLATE TUBE ENDS.

FIG. 429



INSIDE TYPE. MACHINED SOCKETS. OUTSIDE TYPE.

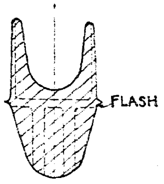
FIG. 430

in pairs and one channel. The material is mild steel to Specification S3. The main load is taken on the two flat pieces which are slotted into the tube and welded, the welding being in shear. The two side plates and the channel are thinner, and serve to seal the tube end. They do, however, take load in proportion to their thickness, transmitting it through the weld to the tube. In fittings of this kind it is frequently found that the plate is down in bearing strength. Washers are therefore welded on as shown, and increase the bearing strength in the proportion of their thickness to the total thickness. They are welded in position. If the tube is a tension member, or at any time carries a tensile load, it is sometimes the practice not to weld right round the end of the fitting. The value of this precaution is doubtful, as the annealing effect of the oxy-acetylene flame extends up to an inch or more from the weld.

Owing to the manufacturing tolerances on sheet metal and the slight distortion caused by the welding, it is impossible to work to close limits on the width of the fitting. The final exact dimension of width may be obtained by filing down the surface of the washers or of the channel piece.

To reduce distortion and avoid cracking, the thickness of any of the individual plates should not be more than two or three gauge sizes above the wall thickness of the tube.

An end fitting of this kind must be normalized to relieve the internal stresses caused by bending and welding, and to restore the material to its full strength. It is therefore not suitable for struts outside the normal muffle furnace length, and it restricts the tube to one of the low tensile welding grades such as T45.



DROP FORGED BLANK FOR STRUT END SOCKET.

FIG. 431

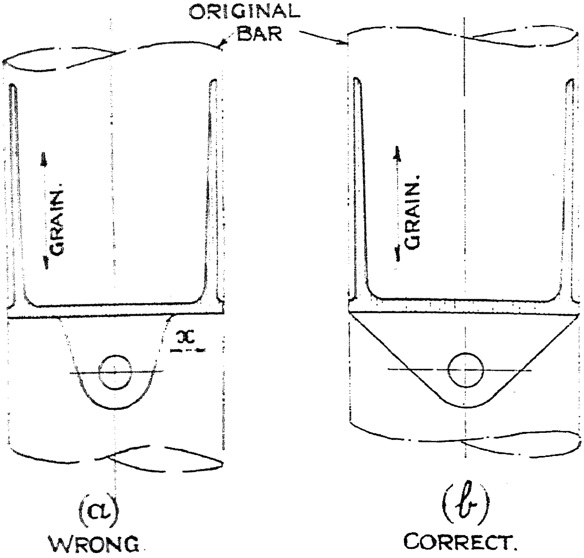
If the tube is duralumin or one of the higher tensile steels, the fitting must be machined as shown in Fig. 430. In a large production where standardization of tube sizes and end sockets may be effected it will probably pay, both in material and labour, to use drop forged blanks rather than round bar parted off to length. A suitable blank for the socket *b* is shown in Fig. 431. The saving in material may amount to 20 per cent, and if the forging is well done the outside surface may require no treatment beyond the removal of the "flash" by grinding and descaling by pickling or sand blasting.

There are adherents to both the inside (*a*) and outside (*b*) types of sockets. The outside type gives an appearance of better finish, but requires a blank of slightly larger diameter. It has the additional but small operation of drilling an inspection hole for the purpose of ensuring that the tube extends the correct distance into the socket. The internal socket requires slightly less material and gives a more flush job. Greater care must be taken in cutting the tube end, and its inner edge must be radiused or bevelled. The great difference between the two types, however, is due to the tolerance in tube size. In standardizing sockets only one tolerance, that on external diameter, has to be catered for in the outside type. With the inside socket there are two tolerances, that on the tube diameter and another on the tube wall thickness. Inside sockets made to close limits will vary from a drive fit to a sloppy one, according to the variations in the tube. And if made to big limits they may refuse to marry up with a particular piece of tube. This, more than any other reason, is the best excuse for the outside socket, and it is an excellent illustration of the influence of interchangeability limits on detail design.

The joint is completed by fastening with taper pins. The pins must be designed to carry the full load in the member. No credit for strength may be given to the bearing of the tube end on the socket, as very exact and unnecessarily expensive work would be needed to make it a good enough fit.

The taper pins are put in at an angle of 90 degrees if two are used 60 degrees if three, and so on, in order that the stress may be evenly distributed.

A point which is insufficiently realized is that there is a distinct "grain" in steel. In a rolled steel bar it is marked by the intergranular inclusions which run the length of the bar. The machined fittings just discussed were made from round bar, and the grain therefore runs from top to bottom of the socket. Had the tube been of larger diameter and the end jaws smaller, the socket might have been designed in one of the two ways shown in Fig. 432. Assuming the socket was machined from bar of the same outside diameter, the centre line of the two being identical or parallel, the grain would run the direction shown by the shading. There would then be a most definite weakness in (*a*) at the point *x* over and above that which would be there if the material were uniform. The jaw webs should go to the rim of the flange so that the path of the load may run straight to meet its reaction in the barrel of the socket.



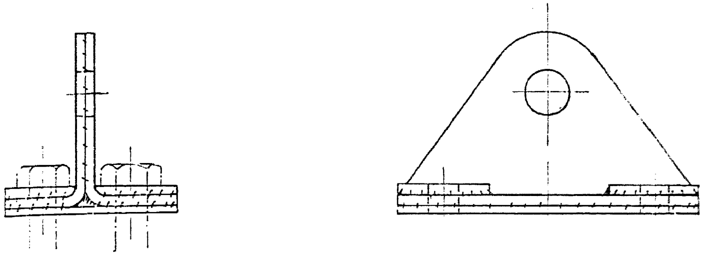
EFFECT OF GRAIN IN STEEL BAR.

FIG. 432

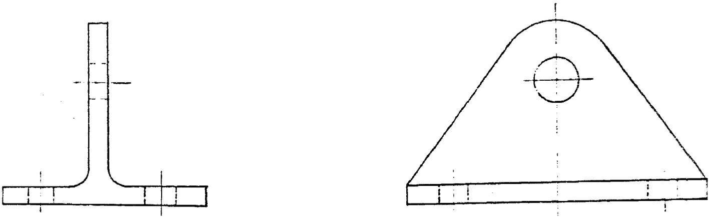
Compare the plate and machined ⊥ fittings in Fig. 433. The question of grain is not so important in the former. The internal structure of the material runs parallel to the surface and follows the bends. But in the machined fitting the radius in the corner should be generous so that there is no concentration of load at the point where the grain becomes short. If possible, the machined fitting should be made from a drop forged blank, in which case the grain flow would be correct. Fig. 434 illustrates the flow in a valve stamping which is of a similar nature to that required in the ⊥ fitting.

The importance of this point is shown by the following tests[1] on samples cut with and across the grain—

Material	Maximum Stress, Tons per sq. in.		Reduction of Area, per cent		Izod, ft.-lb.	
	Long.	Trans.	Long.	Trans.	Long.	Trans.
Nickel-chromium steel (heat treated)	64·8	65·8	61·0	35·7	57·0	18·0
Duralumin . . .	26·3	19·1	38·9	8·9	—	—
Magnesium alloy (forged) .	18·9	16·7	20·6	9·1	—	—



BENT PLATE ⊥ FITTING



MACHINED ⊥ FITTING.

FIG. 433

Returning to the bent plate ⊥ fitting (Fig. 433), a small but very desirable feature is the fitting of thick washers under the holding-down bolts. These allow the bolts to be brought close in the vertical web and to overhang the radius of the bend, thereby increasing the stiffness of the fitting appreciably.

A comparison in cost between bent plate and machined ⊥ fittings would be interesting, but must, of course, be worked out for each factory owing to the variations in overhead charges, available plant, and so forth. In the plate fitting there are seven pieces which must be cut to shape, bent and filed to fit. Pilot holes must then be drilled,

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[1] Johnson, "Inspections of Metals and their Alloys," *Journal R.Ae.S.*, June, 1930.

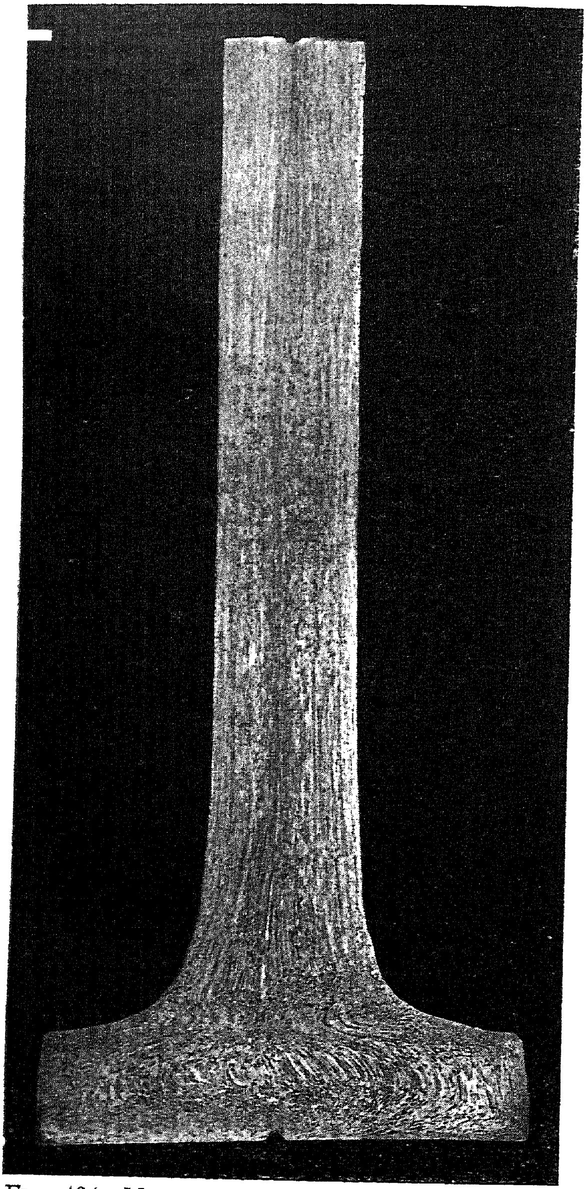

FIG. 434. MACRO-SECTION OF VALVE STAMPING

(*By courtesy of the English Steel Corporation, Ltd.*)

the fitting bolted together and passed to another operator for welding. It is normalized and sand-blasted before drilling and corrosion-protection, which are operations common to both plate and machined fittings. In addition, therefore, to the seven pieces of material which go to make the complete fitting, there are upwards of half a dozen operations to be performed. The time taken in normalizing and cooling off, as well as the waiting intervals between operations, keep the fitting under an overhead charge considerably longer than in the case of the machined piece.

The latter would pass through more quickly, as there are only two, or at most three, stages of milling before the drilling and corrosion-protection operations. More material is certainly cut to waste, to balance against the extra operations and time of the bent plate work. But it must not be assumed that because the material is inexpensive, and the finished article looks cheap, that the plate fitting is less costly than the machined one.

Turning now from the manufacture of a single fitting to mass production, three press tools are required for the plate work against a single but more expensive die for making a stamped blank of the other. Again it is unsatisfactory to generalize, and detail costs should be worked out for a number of examples before making a decision.

So far it has been assumed that mild steel was the material of the ⊥ fitting. In high-tensile steel or duralumin the angle plates and base could not be welded together. They would have to be drilled and riveted and the packing washers under the heads of the holding-down bolts left loose. The corresponding high-tensile machined fitting would also need a slightly different treatment. The web and base would be thinner and finer limits worked to. The finish must also be much better.[1]

So far only the fringe of detail design has been touched on, but the two examples taken, the strut end and the angle piece, may indicate a method of approach to the problem and show some of the difficulties. They should be taken in conjunction with the analysis of actual fittings in the wing and fuselage chapters.

Stamping, Pressing, and Drop Hammering

The processes of stamping and pressing are amongst the most useful known to engineering. Once the dies are made, the cost of operation is small and the working expense in each part produced negligible by comparison with that of hand manipulation. Moreover, exact similarity and interchangeability is achieved. The objection, of course, to the universal adoption of pressing lies in the cost of the dies. These are usually made of a high quality steel, and although the first rough work in making them may be done by drilling and machining, the finishing and fitting together of upper and lower halves must be by hand scraping.

The cost of making such a die for producing fifty small components may be five pounds. The cost per component is thus two shillings. If the number of components to be produced amounts to a thousand, the cost per component is little over a penny.

Until the R.A.F. rearmament programme began in 1935–6, the process of pressing was, therefore, slow in coming to English aircraft factories except as applied to a few standard sizes of flanged lightening holes

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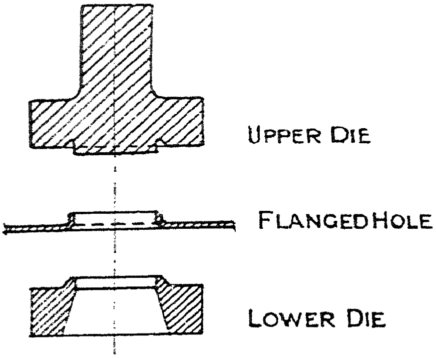
[1] See p. 41, second paragraph.

(Fig. 435) and small standard fittings such as wiring lugs, shackles and washers which may be made in one operation in a hand-operated fly press.

There is, however, much scope for ingenuity in finding cheaper methods of making dies more applicable to the comparatively small production of aircraft parts.

One method developed in America and since adopted in England is that of using a blanking die in conjunction with a block of confined rubber in the operating head. The lower surface of the table is flat and the operating head is made hollow to receive the rubber block. The male die is cut from zinc and the sheet metal blank pegged on to it. This is set on the table, the operating head comes down under hydraulic pressure and the rubber forces the sheet metal round the die so that it completely takes the outward shape of the die and also of any recesses or grooves cut in it.



DIES FOR PRODUCING FLANGED LIGHTENING HOLES

FIG. 435

Flanged ribs and diaphragms made by this process in the St. Louis factory of the Curtiss-Wright Company are shown in Fig. 436. In this example, the dies are made of Masonite, a plastic material which is easy to work and tough enough for the production of at least a hundred parts.

A press used by Curtiss-Wright is illustrated in Fig. 437. In order to justify the expense of such a machine the work must be planned well ahead to keep it fully employed. Three feeding tables are used in turn so that parts may be set up while others are being pressed. The process is thus made economical and quick.

A 3000 ton hydraulic press for this process has been built for the North American Aviation Company of Inglewood, California.[1] The toggle principle is used in order to develop the very high pressure required for forming with rubber. The hydraulic pump is driven by a 150 h.p. electric motor and applies a pressure up to 2000 tons per square inch through an 18 in. diameter ram. The toggles multiply the load by twelve

[1] For further details of this Press see *Aero Digest*, January, 1939.

and the maximum capacity is 8 ft. × 2 ft. 6 in., or 11 ft. × 12 in. The rubber block weighs over half a ton and is 5 in. thick with a section 12 in. wide down the centre, which is 10 in. thick and 11 ft. long. The platen may be moved out from under the press by hydraulic power so that it can be loaded in the open. It is 8 ft. long × 2 ft. 6 in. wide, and has end extensions to correspond to the deeper part of the rubber block. This part is used for pressing long members such as longerons and spar members.

Another similar approach to the subject has also been made in America,[1] and subsequently adopted by British manufacturers. It is described as the "Soft Metal Die Process," and is particularly applicable to duralumin and aluminium parts, such as ribs, formers, cowlings, tank ends and baffles, etc. The following description will be clearer if the part being made is imagined as the bulged end of an aluminium tank.

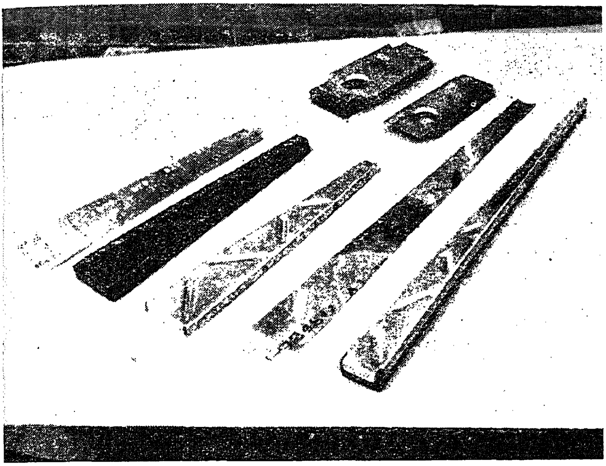


FIG. 436. MASONITE DIE WORK

(By courtesy of Curtiss-Wright Corporation)

Two battens are clamped to a table at right angles to each other in the form of a cross. On these are set up two crossing templates, in thin sheet metal, of the tank end contour. The quarters are then filled in with clay and swept off to shape so that a complete hollow mould of the tank end shape is quickly obtained. A plaster impression of this is taken and used as a pattern for casting the female die in zinc, the finish being usually good enough without either scraping or machining. The die is set up on the anvil of the press, which may be of the drop hammer, hydraulic or toggle types. It is raised on four small wood blocks about ¼ in. above the surface of the anvil, in which are four or five ½ in. holes. A wall of clay or wood is put up round the die, ½ in. away from it and 2 in. high. Molten lead is poured into this gap so that

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[1] "The Construction of the Metal Airplane," by Mr. George H. Prudden, of Bristol, Pa., before the American Society of Mechanical Engineers' National Aeronautical Meeting, Baltimore, 12th–14th May, 1931.

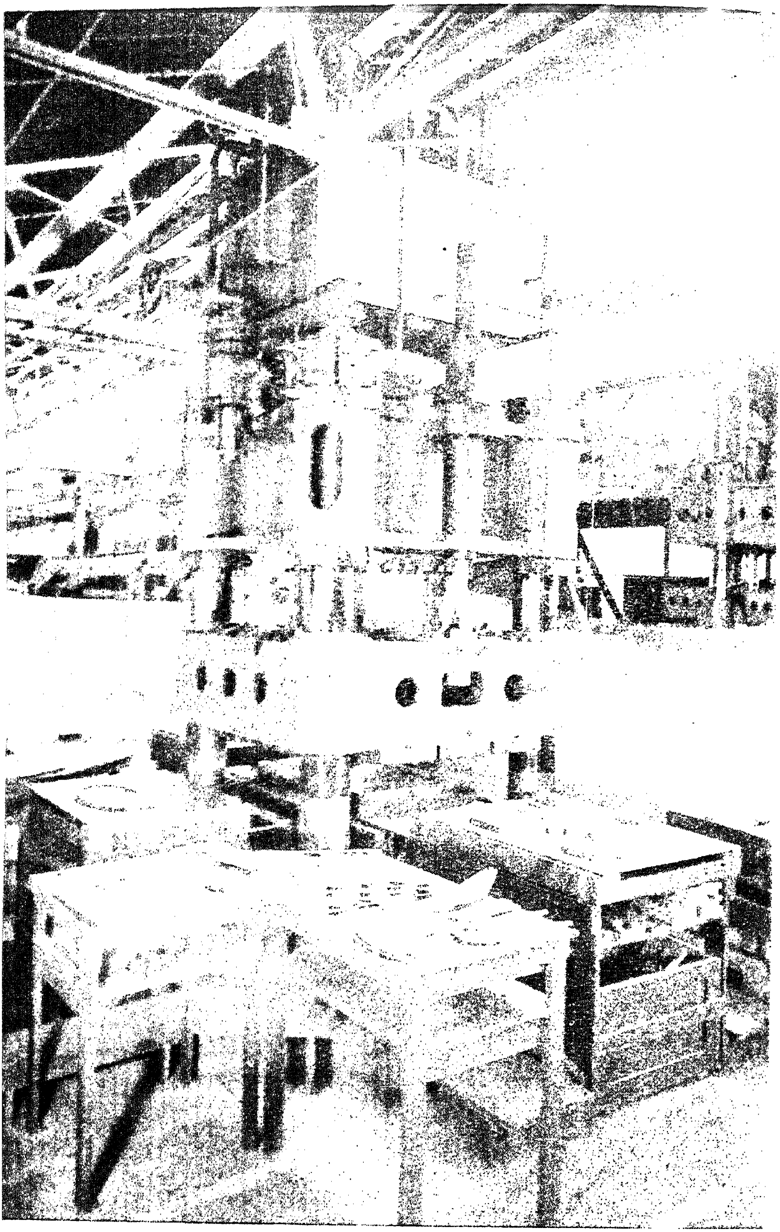

FIG. 437. CURTISS-WRIGHT HYDRAULIC PRESS
(By courtesy of Curtiss-Wright Corporation)

it runs between die and anvil into the holes, at the same time forming a flange round the die and locating it.

The upper half of the die has now to be made, and may be cast in position. A strip of flexible sheet metal is lashed round the anvil die, projecting above its surface. Into this molten lead containing a little antimony is poured. Whilst it is still molten, the hammer, which has four or five rag screws projecting, is let down into it. The sheet metal casing is removed as soon as the die has set, and on lifting the hammer the upper die travels with it, supported on the rag screws.

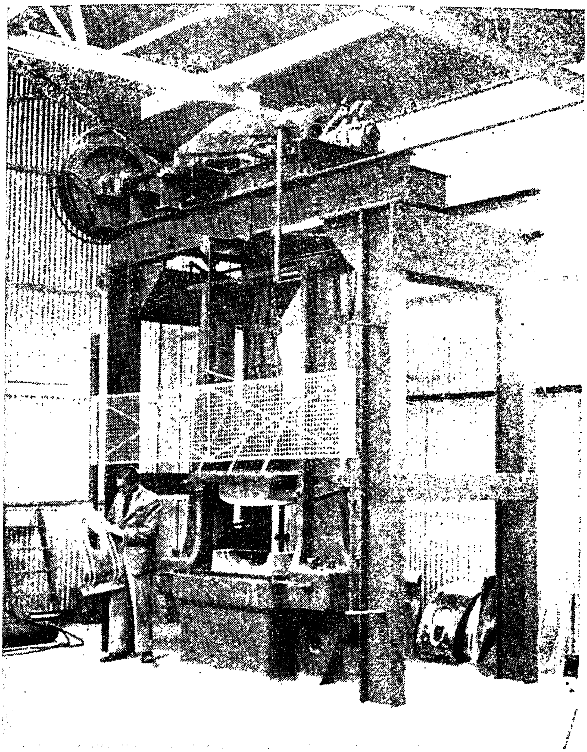

FIG. 438. DE HAVILLAND DROP HAMMER
(*By courtesy of "The Aeroplane"*)

The one die having been cast in the other, there is no clearance between them. A sheet of soft iron of the same thickness as the tank ends is inserted between the dies and stamped. It is just sufficiently tough to create a clearance automatically. It may be taken out. flattened, and used as a template for blank cutting. Dies of this kind are said to be satisfactory for fifty to sixty parts. They are then remelted and the material used again. The pattern, of course, is kept and always available.

In the making of more complicated parts, where deeper drawing and finer limits are required, lead is not good enough for the male die and both must be of zinc. It is found possible to make this in the same way as the lead die was made, there being no adhesion between the two zincs. Any trouble of that kind could always be met by using the plaster pattern. If the die is deep it should be designed with a taper to allow withdrawal of the upper one. Double zinc dies have been found interchangeable and more accurate than if made by hand. It is, of course, infinitely cheaper than beating, even when the number required is a dozen or less, particularly as the patterns, once made, are always available and the zinc quickly melted up for use again.

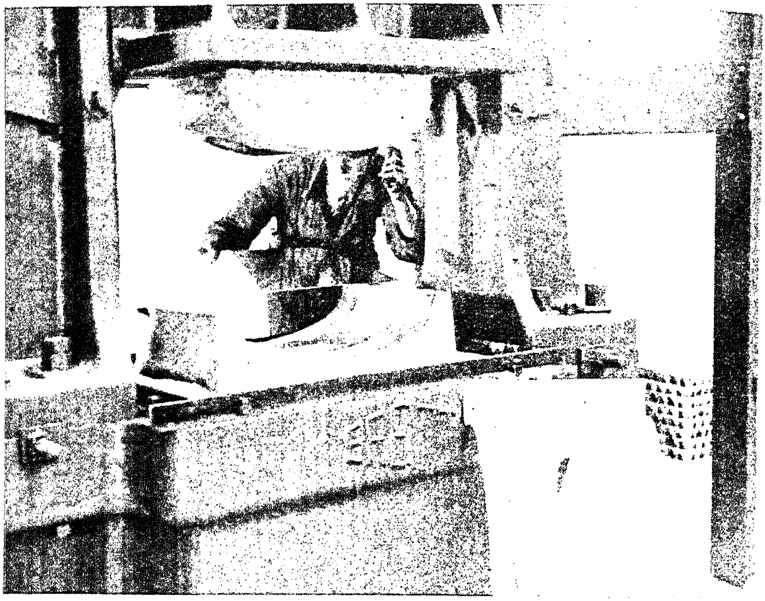

FIG. 439. DE HAVILLAND DROP HAMMER
(*By courtesy of "The Aeroplane"*)

A drop hammer used for this process by the de Havilland Aircraft Company Limited is illustrated in Figs. 438 and 439.

The tup of the drop hammer with the punch attached weighs about 1½ tons, yet the operator has a finger-light control of the force of its blows, and shapes the metal with a succession of light taps. The flow of the metal is helped by smearing both punch and dye with high-pressure grease. Slight folds and ridges caused in the flowing of the metal are afterwards levelled out by using the high-pressure pneumatic planishing hammer. The rapidity of production is, of course, much greater than the older methods of hand working. One end panel of a de Havilland petrol tank which took twelve man-hours to shape by hand can be turned out in thirty seconds. This press is operated by means of a 30 h.p. electric motor.

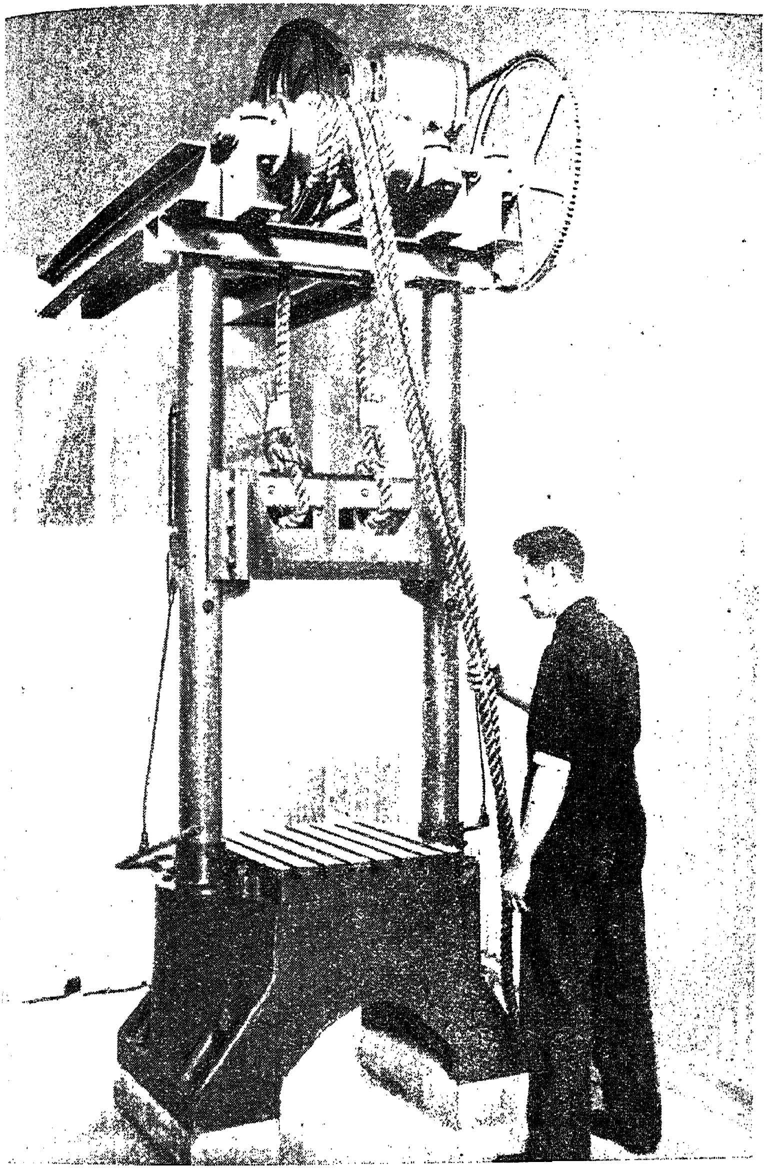

FIG. 440. GENERAL AIRCRAFT DROP HAMMER

(*By courtesy of General Aircraft Limited*)

A much smaller hammer, having a base 24 in. square, is shown in Fig. 440. This is the smallest in a range of hammers produced by General Aircraft Ltd. It is capable of producing small fairings and fittings such as are shown in Fig. 442, the material being aluminium alloy. A suitable oil-fired furnace for melting down the spelter for casting is shown in Fig. 441. This has draw-off valves at different levels so that the pure metal free from dross can be run into the mould.

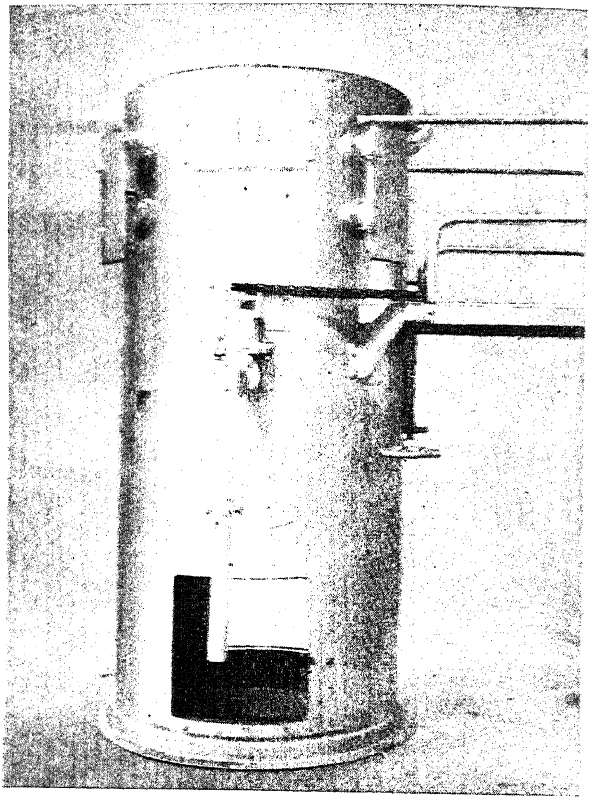

FIG. 441. OIL-FIRED FURNACE FOR SPELTER
(By courtesy of General Aircraft Limited)

When sheet duralumin is hammered it should be in the heat-treated condition, i.e. it should have been raised to 490° C. and quenched. The parts should then be pressed within an hour or two.

If, however, it is proposed to use the drop hammering process for shaping elektron, there is some difficulty since this material should be worked at a temperature of 250° C.–300° C. For this purpose, therefore, dies of cast elektron have been developed in Germany.[1] The best form of elektron for die-making is the alloy known as A.Z.G., which is moulded in steel crucibles and cast in sand at a temperature of 650°–680° C. The durability of these dies is said to be quite adequate for the present rate of production and they may be used for 500 to 1,000 pressings on the drop hammer. Elektron dies are, of course, much easier to handle than those made of spelter.

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[1] See *Aircraft Production*, December, 1938, "The Preparation of Elektron Dies," by O. Oeckl.

A large hydraulic press used in the Curtiss-Wright Buffalo plant is shown in Fig. 443. This has a capacity of 2,500 tons. The bed and platen are over 6 ft. wide and 12 ft. long. The maximum opening is 52 in., and the stroke 43 in. The press may be used with male and female dies of metal-covered wood, or of zinc and lead. Alternatively, it may be used with a female die and a rubber head.

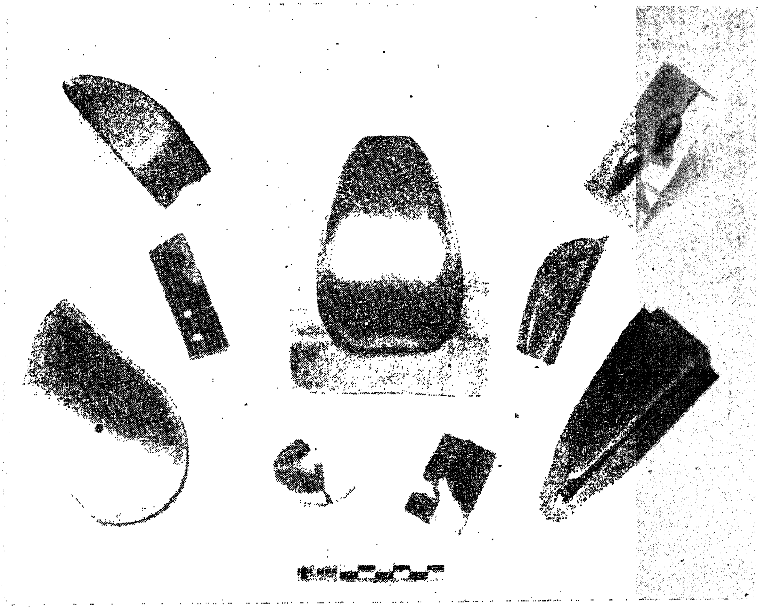

Fig. 442. Typical Fairings made on Drop Hammer

(By courtesy of General Aircraft Limited)

Another machine for forming sheet metal for aircraft work is the drawing and stretching press. This is different from the better known drawing press in which sheet metal is pushed into an opening on a die by means of a punch, in that it is stretched over a former. A stretching press is illustrated in Fig. 444.

The table of the press rests on the piston which moves upwards in a corresponding cylinder under the action of fluid pressure. On either side of the table are grippers on which are assembled clamping jaws which hold the sheet metal. A former corresponding to the shape of the component to be made is fixed on the table. The blank cut to size and greased is laid over the former and clamped on both sides by the grippers.

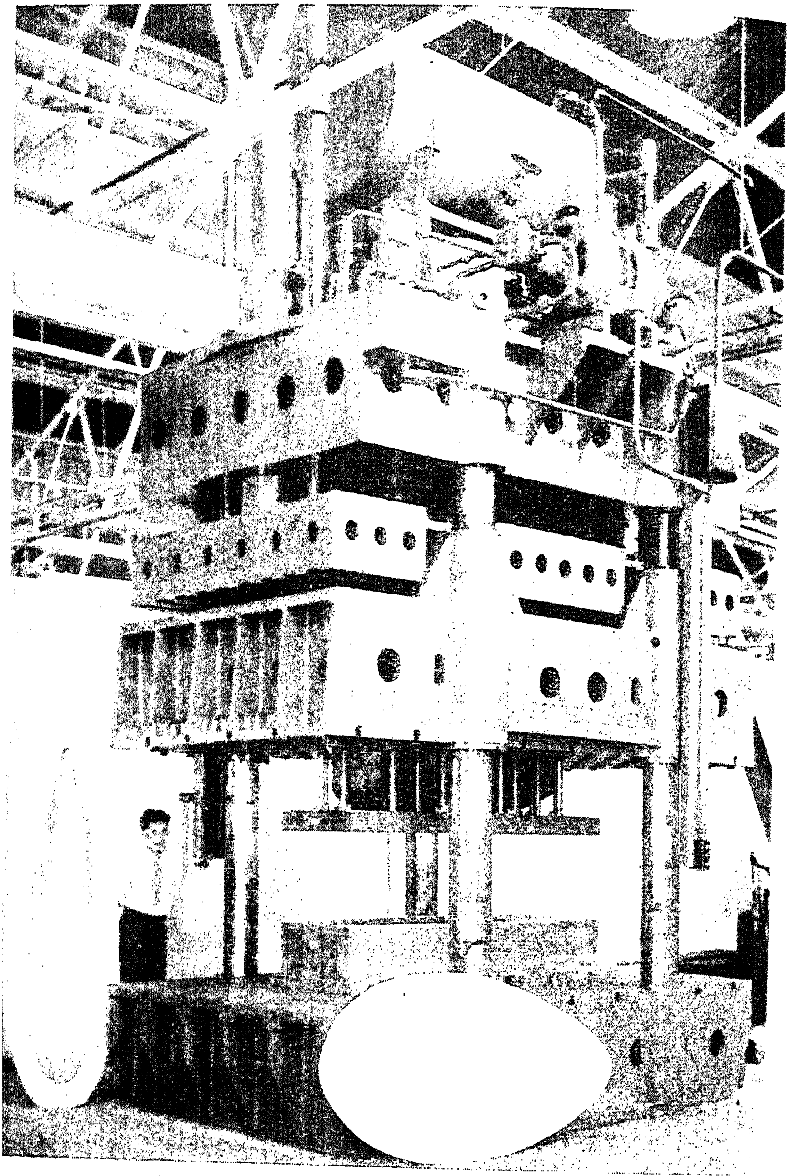

FIG. 443. CURTISS-WRIGHT HYDRAULIC PRESS
(*By courtesy of Curtiss-Wright Corporation*)

After engaging the pump and opening the control, the piston rises, pushing the former upwards against the sheet metal blank, thus the sheet held by its ends is stretched over the former.

The stroke can be automatically limited so that the table movement stops when the part has been adequately formed.

The formers may be made of hardwood, such as copper beech, or from compressed wood or reinforced synthetic resin. When "Elektron" is being stretched the former should be made of metal owing to the high temperature at which the elektron must be worked. The surface of the former must be polished to avoid frictional resistance.

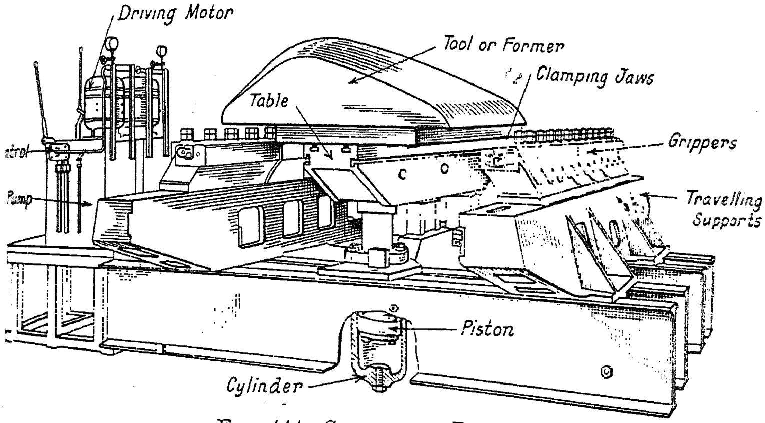

FIG. 444. STRETCHING PRESS

In some cases where parts cannot be completely stretched to their final shape, they can be prepared on this machine and then whilst still under tension or on a special former finished by hammering. Where, for example, grooves are required, these may be cut into the former and faced with metal, as shown in Fig. 445, so as to withstand the subsequent hammering.

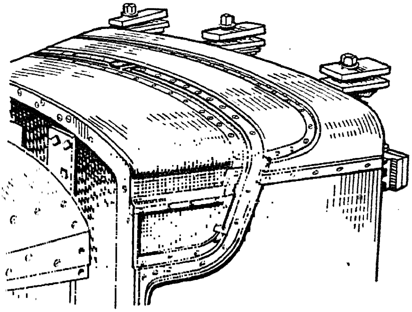

FIG. 445

Duralumin parts are normally made with the metal in the heat-treated condition, but extra cheap drawing may be achieved by putting the material through the annealing process several times.

Cheap and satisfactory processes on these lines should have a revolutionary effect on aircraft constructional design if full use were made of them in all possible places.

SPINNING OF ALUMINIUM AND ALUMINIUM ALLOYS

General. The spinning of aluminium and aluminium alloys is adopted to a considerable extent in the production of aircraft parts because of the low cost of the chucks employed as compared with the high cost of press dies. Where a small number of articles is required it is more economical to produce by spinning even if the shape is simple, while if the shape has a complicated re-entrant outline, spinning may be recommended even when large numbers are required because of the excessive cost and number of operations involved in production of pressings. In some cases, spinning is used as an adjunct to the press, the latter being used for producing the initial shape and more complicated work carried on the lathe. The following notes on the subject have been prepared by the London Aluminium Co., Ltd., of Witton, Birmingham, who specialize in this work.

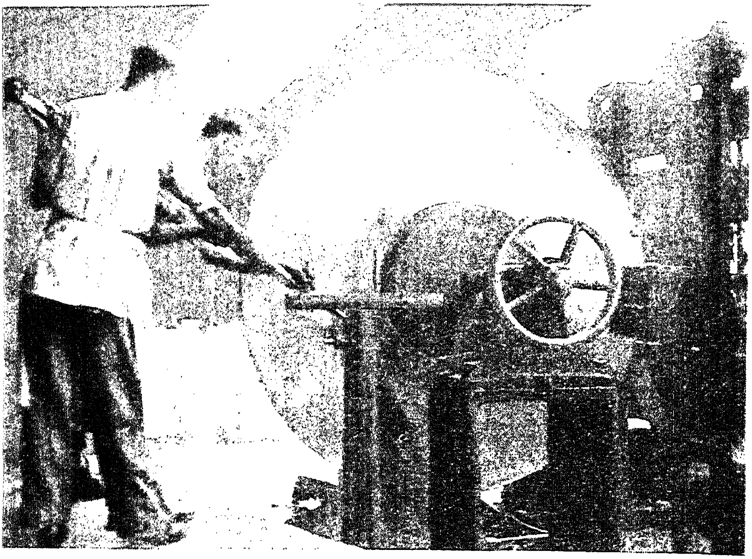

FIG. 446. AN INDICATION OF THE POSSIBLE SIZE OF SPINNING WORK

Two operators are occasionally necessary when dealing with large diameter heavy gauge jobs

(By courtesy of The London Aluminium Co. Ltd.)

Operation of Process. The actual process of spinning consists of forcing a sheet metal blank over a former by using hand tools. The metal blank is held against the former or chuck by means of a centre piece carried in the lathe tailstock and a lever motion is applied to the tool using a pin in the lathe-rest as a fulcrum (see Fig. 446). Because of its high ductility aluminium is particularly suitable for spinning work, which is, of course, carried out at air temperatures. Complicated shapes can be spun from aluminium without intermediate annealing and this applies to certain of the aluminium alloys. Aluminium manganese alloy can be spun with practically the same ease as pure aluminium, but aluminium silicon alloy hardens up much more rapidly and much less work can be done before the metal is hardened to the extent of cracking.

With the heat treated alloys it is essential that the metal should be in the annealed state and even then only a limited amount of spinning is possible. Aluminium is usually spun at a peripheral speed of about 3,000 ft. per minute, which on an 8 in. to 10 in. diameter chuck is equivalent to 15,000 r.p.m. or with an 18 in. to 20 in. chuck about 5,000 r.p.m.

The material for the chuck depends on the number of spinnings to be produced, but where only one or two are required, comparatively soft wood may be adopted while for bigger quantities it is usual to work on either beech or lignum vitae. Where appreciable quantities are required regularly, it is usual to manufacture iron or steel chucks. The tools used are of steel and consist essentially of shaping and planishing tools, the first operation gives the shape required with a certain amount of ridging due to the edge of the tool. This is finally removed by planishing with a special tool when a surface almost as good as that of the original blank can be obtained. In addition various tools are necessary for the trimming, beading, etc., of the metal edge after completion of the spinning.

Lubrication of the blanks is, of course, essential both before and during spinning. The normal lubricants used are vaseline, lard oil, tallow, or similar material.

Design Points. In estimating for the production of a part by spinning, the designer must realize that although the spinner has a certain amount of control over the final thickness of his work there is a certain amount of metal lost in shaping by this process. For example, if a complicated shape is to be produced, the metal will thin down appreciably towards the edges of the spinning and also during the planishing process. This reduction in thickness may amount to one or more gauges and, therefore, it is essential in some instances to start with a blank which is thicker by several gauges than the finished article. If this is done, it can then be assured that the minimum thickness will not be less than that specified for the part. The excess metal thickness on parts which have little or no labour, i.e. flat surfaces, can be reduced to a comparable figure by final planishing.

As the metal hardens during spinning, it is essential to start with a blank of the correct temper, thus with a complicated shape it may be necessary to start with a dead soft blank while comparatively simple shapes can be spun from medium or even medium hard temper. This point is important as if the metal is stressed beyond its natural hardness its fatigue strength is appreciably lower and cracking will take place. It is also essential that the designer decides on the number of spinning operations involved in the production of the finished part. In the case of complicated shapes particularly with re-entrant curves it may be more economical to spin these in two or more operations, using a straight chuck for the first operation and section chucks for the later ages.

In regard to blank size, the general rule is to take the area of the finished article as being equal to that of the blank, but in the case of complicated shapes this gives an oversize figure since during spinning the parts, as mentioned above, are reduced in thickness, which gives an equivalent increase in area and causes waste of metal in the final trimming.

Applications. The process has many applications, the most obvious ones being in the cowling of radial engines (as in Fig. 447), airscrew spinners, landing light reflectors, and fairings. Circular spinnings may be cut down into a number of wheel mudguards or they may be subsequently shaped by hand or press into undercarriage spats. Fig. 448 shows some large air ducts made in halves or quarters and welded up. Similar parts on a smaller scale might be used in the ventilation or heating ducts of passenger cabins.

Electric Spot Welding

Electric spot welding is a process whose possibilities for metal aircraft construction are now realized. In steel and strip structures such as spars, ribs, and built-up struts, it would seem to offer a substitute for riveting. Spot welds have been shown to have a similar strength in shear to rivets of the same diameter. Against the expense and time of drilling the holes, inserting and hammering up the rivets, the cost of welding is inconsiderable. In joining two thicknesses of 20 s.w.g. mild steel together over 6,000 welds may be made per K.W.H. The speed of working is also much quicker, as only a fraction of a second is taken in the actual making of the weld. The time factor is really a function of the speed at which the operator can pass the material through the machine and make contact. The process would appear particularly suitable for stainless steel sheet and strip where riveting difficulties are increased by work-hardening of the material. If ordinary high-tensile steels are spot welded, the rapid cooling which follows by conduction has the effect of embrittling the weld. There is one point over which the spot welding method fails, as yet. It has not been found possible to develop the same strength against vibratory and fatigue stresses as in a riveted structure. When this difficulty has been overcome the possibilities seem big.

In the simplest form of the process the parts to be welded are clamped together and a heavy current of low voltage passed through the steel between the tips of two high-conductive electrodes which are brought into contact with it. The resistance of the laminations is greater than that of the electrodes, and heat is at once generated which fuses the thicknesses together. The time taken for this to happen varies as the resistance, but for aircraft strip it is a small fraction of a second. In the older methods of spot welding the time was under the control of the operator, which is, of course, unreliable with such short intervals. Automatic controllers are now fitted which cut off the power at some predetermined product of time and current. If, therefore, a few tests are made the appropriate setting of the automatic controller can be found.

In a foot-operated machine the lower electrode is fixed. The upper electrode is on a hinged arm which moves down under the action of the foot pedal. The first portion of the pedal's travel moves the electrode down and clamps the work between the tips. The second portion of the travel switches on the current. As the material softens the pressure of the electrodes causes a slight indentation on the surface.

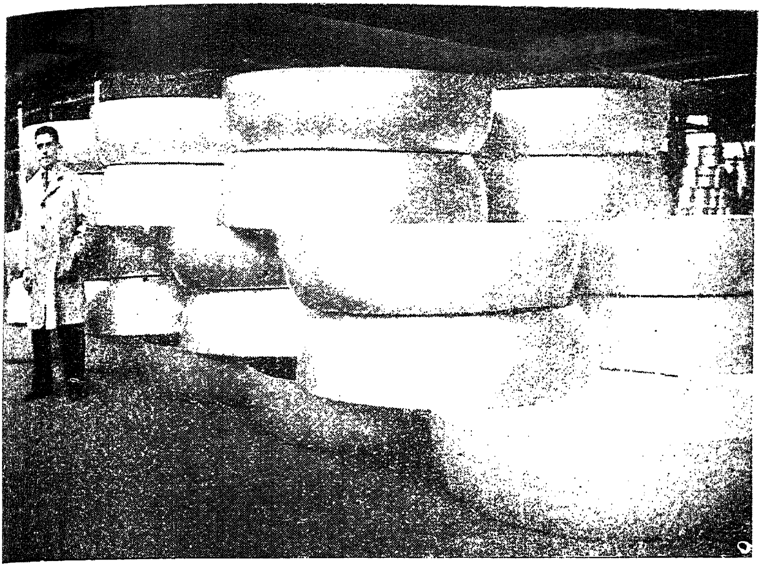

FIG. 447. LARGE SPINNINGS FOR FAIRING RINGS

(By courtesy of The London Aluminium Co. Ltd.)

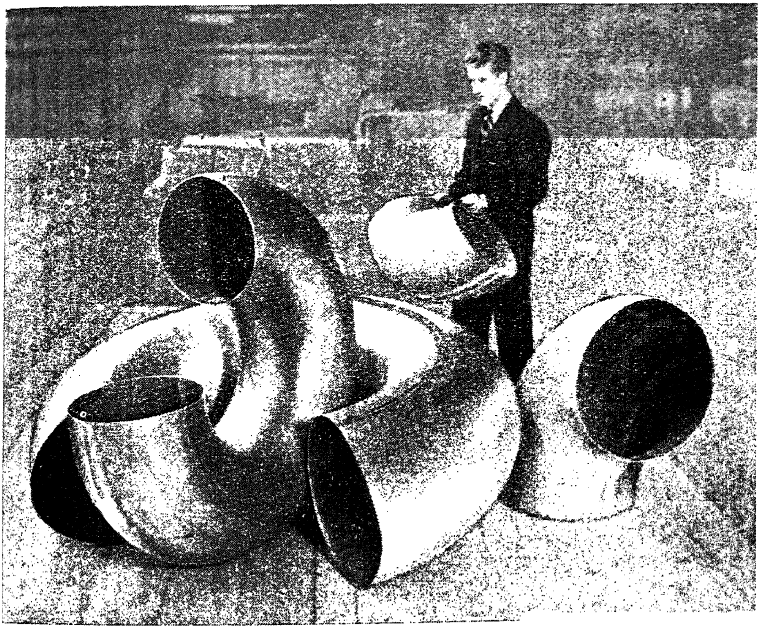

FIG. 448. SECTIONS OF AIR TUBE MANDRELS AFTER SPINNING AND WELDING

(By courtesy of The London Aluminium Co. Ltd.,

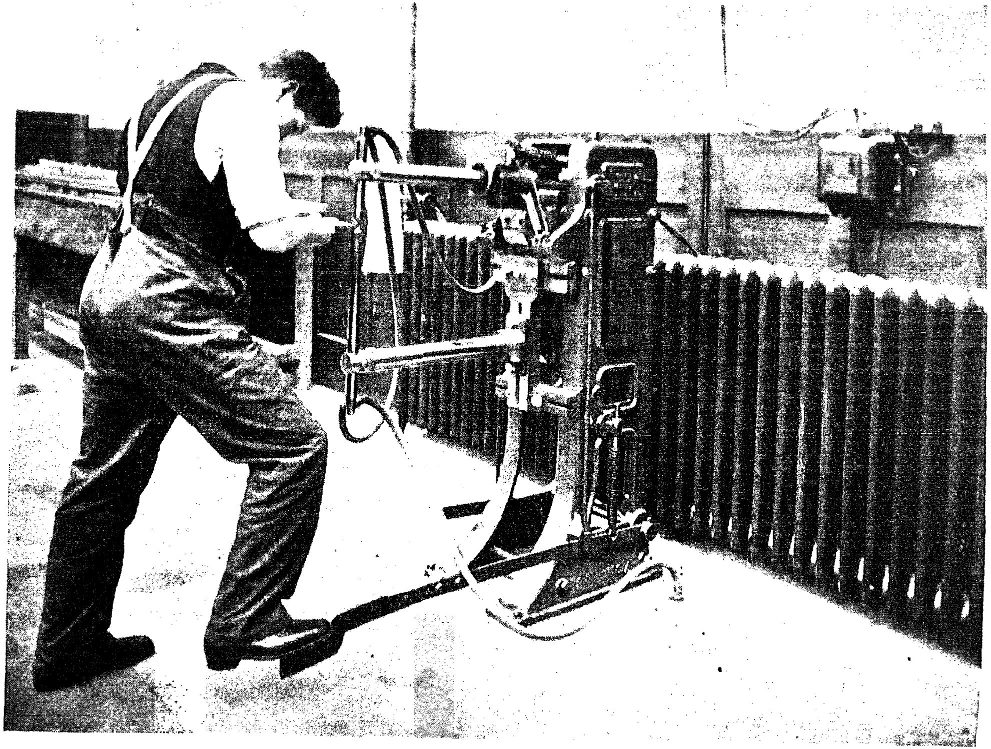

FIG. 449. SPOT WELDING MACHINE

A good weld takes the form shown in Fig. 450, from which it will be seen that the "slug" of welding is quite internal and does not extend to the exposed surfaces.

If the fusion zone extends to the surface there has been faulty adjustment of the time-current product, resulting in overheating. In welding stainless steel sheet the indenture on the surfaces opposite the weld may be slightly discoloured by a film of oxide. This is easily removed with metal polish and the non-corrodible properties of the sheet are not affected.

If the welds are made close together there does not appear to be any tendency for the current to run back and pass through the nearest weld. In tests made with a "Budd Shot Welder" on ten samples of D.T.D. 60A. sheet 0·032 in. thick, the average shear strength was 687·5 lb., and the greatest variation from the mean was not more than 6·5 per cent. Tests on groups of three welds close together in the same material gave a consistent strength of 660 lb. per weld, which is within the limits of the ten single samples. Two tests on dirty samples also gave results well within the limits. The presence of some foreign matter such as oil, or even paper, between the plates does not affect the result.

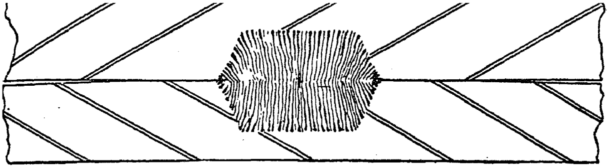

FIG. 450

(*By courtesy of "Flight"*)

In comparing these figures with the strengths of similar riveted joints it should be realized that the number of welds in a given length can be increased much more easily and cheaply than can the number of rivets, and that closely-spaced welds do not lead to loss of efficiency. Experimental units and components such as ribs, spars, and complete seaplane floats have been made of stainless steel in England, using both Budd and A1 welding machines. In America a complete flying boat, modified from the Savoia-Marchetti S-56, was built in 1931 by the Budd process from stainless steel. This boat has been demonstrated both in America and Europe.

The growing popularity of the "metal clad" wing and fuselage made of a light alloy such as duralumin draws attention to the possibilities of using resistance welding in the fabrication of such structures. It is an essential feature of stressed skin construction that the stresses be low. The use of a high tensile material is, therefore, only economical if it is kept very thin. The extra bulk for the same weight which is implied in the use of a light alloy gives greater stability to a duralumin structure of this sort.

A number of firms, including the Sciaky Company and Phillips Industrial, have been working on the problem of spot-welding duralumin. If this can be applied to the monocoque fuselage or stressed skin wing, the advantage would be aerodynamic as well as economic. Both the weight and the air drag of the rivet heads would be eliminated, and the speed of welding is many times greater than that of riveting.

So far the great difficulty in the application of resistance welding to duralumin has been in the preservation of the mechanical properties of the material after the application of heat. Ordinarily the internal structure of the material breaks down at a temperature of about 515° C. This difficulty may be overcome if a particular cycle of mechanical pressures between the electrodes is associated with the current cycle. Duralumin, like all the aluminium alloys, has a high conductivity to

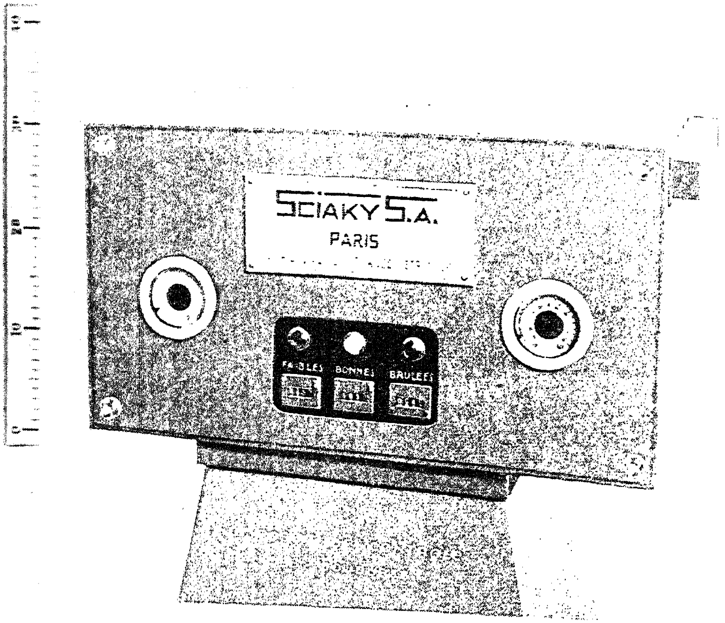

FIG. 451. SPOT WELDING CONTROL

A.—If the weld is below normal, a green lamp is lit and a bell rings. The counter adds up the number of weak welds.

B.—If the weld is normal, a white lamp is lit. The number is similarly recorded on a second counter.

C.—If the weld is over done, the red lamp is lit and bell rings very loudly. A third counter adds up the number of these welds.

In the case of *A* and *C*, the machine is automatically stopped so that the operator may examine the electrodes to see if they are worn, etc. The foreman may be called before permission to restart the machine is given.

(By courtesy of Soudeuses Electriques Sciaky, S.A.)

electricity, and also to heat. It is, therefore, difficult to raise the temperature of the material between the electrode points.

There are differences in detail between the Sciaky and Phillips methods and each claims certain advantages. Without pretending to judge between them, the description which follows applies more particularly to the Sciaky process.

Before the current is turned on, the electrodes bring together the two thicknesses to be welded. This pressure is relieved as the current is switched on. The plates tend to spring apart and the slight gap between them, minute though it is, creates the necessary resistance. The time of passage of the current is very short and varies between one hundredth and twenty-hundredths of a second, according to the thickness. As the current is cut off automatically, the mechanical pressure between the electrodes is applied again. This may be as much as 35 tons per sq. in. The Sciaky welding machine incorporates a pneumatic relay, for although the electrode points are brought together by the use of the operator's foot control, the actual pressure is subject to the initial adjustment of the machine.

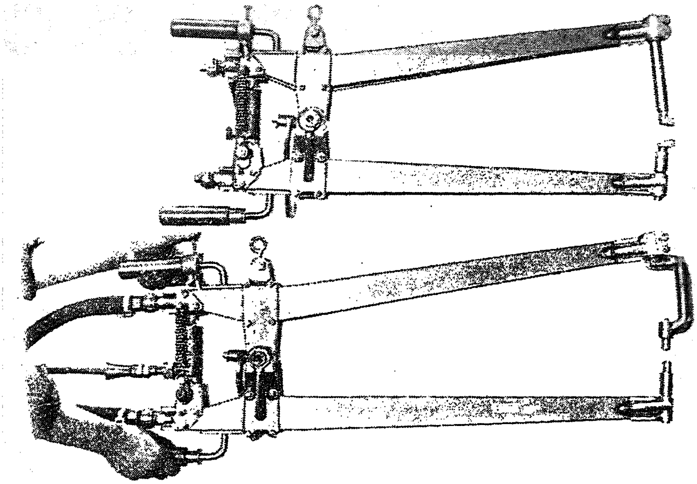

Fig. 452. Long Pincers for Sciaky Method of Spot Welding Hulls, Fuselages, etc.

(By courtesy of Soudeuses Electriques Sciaky, S.A.)

The automatic control is very necessary as the welding times must follow a definite law if the material is to regain any of the qualities which it loses in the high re-heating temperature. The controlling apparatus is so designed that it warns the operator by turning on a coloured light and ringing a bell if for any reason the weld is not perfect. Further, it can be arranged to stop the machine automatically so that the condition of the electrodes can be checked. This implies deliberate re-starting after a faulty weld. Mechanical counters are fitted which add up separately the numbers of weak, good, and burnt welds (see Fig. 451).

The following data on the shearing strengths of spot welds have been supplied by the Sciaky Company—

"Each test piece consisted of two thicknesses of normalized duralumin or of vedal.[1] They were tested by gripping the two extremities in the jaws of a tension machine so that the welds were in shear. The degree of uniformity was established by repeating each test on fifty identical pieces."

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[1] Vedal is a French material similar to Alclad, having a strong aluminium alloy core with surface coatings of pure aluminium.

	Thickness	Number of Spots	Shear Strength	Degree of Uniformity per cent
	in.		lb.	
Dur	0·012 + 0·012		562·3	+ 3·2 and − 3·5
Dur	0·023 + 0·023		617·4	+ 5·5 ,, − 4·5
Ved	0·031 + 0·031		264·6	+ 5·5 ,, − 4·5
Ved	0·031 + 0·031		1,102·5	+ 4·1 ,, − 3·5
Ved	0·039 + 0·039		220·5	+ 4·5 ,, − 4·0

In addition to the foot operated welding machine of the type shown in Fig. 449, there are also pincer appliances (see Fig. 452) which might be used in the assembly of wings, fuselages, hulls, floats, and so forth. These pincers are quite light and can be moved round the job by a single operator.

There is no danger to the welding operator, for though the current may run to several thousand amperes, the voltage is very small. The electrodes are not therefore insulated.

As spot welding gradually comes in use, a technique is slowly being built up. Some notes on the inspection of welds and on the design of parts suitable for this kind of welding have appeared in an American journal.[1] Marschner suggested that X-ray methods and the microscopic examination of sample welds did not constitute a satisfactory method of inspection. He found a very definite relationship between the diameter of the "dimple" on the surface of the sheet, the weld strength and the welding amperage. From this he argues that for electrode tips of uniform shape, it is possible to predict the strength by measuring the dimple diameter. The diameter is reduced if the pressure is increased unless a proportionately larger amperage is used. An operator cannot, therefore, produce the appearance of a large weld by using a high pressure.

In welding soft materials it is usual to find a slight bulge between the welds, particularly if the weld was made too close to the edge of the sheet or stiffener. This is not thought to be bad unless there are cracks in the bulge.

Marschner suggests that any different aluminium alloys may be welded together, but that Alclad is the most satisfactory material because the electrodes require less dressing when used on it. A further point in favour of Alclad is that the corrosion difficulty is largely overcome, except for seaplanes. Anodized parts cannot be satisfactorily welded together nor can the anodic process be used after welding because of the acid which would be left behind in the joints, thus causing the very trouble it is wished to prevent. If untreated Alclad can be used for the parts, protected perhaps by paint or varnish afterwards, the results should be good. Equally, heat treatment is not good after spot welding. It does not strengthen the weld, and the salts which will enter the joints may cause corrosion.

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[1] "Design for Spot Welding," by C. F. Marschner in *Aero Digest*, October and November, 1939. See also "Studies of the Spot Welding of Low Carbon and Stainless Steels," by Wendall F. Hess, D.Eng., and Robert L. Ringer, Jr. E.E., in *Welding Research Committee of the Engineering Foundation*, 29 West 39th Street, New York, Vol. III, No. 10, October, 1938.

Just as riveting should never be used for joints in tension, so with spot welding. The joints must be so designed as to put the welds in shear.

In order to hold the work together during the welding process a small number of rivets may be used. There should be one at each end of a lap joint, and intermediate ones may be needed if the joint is a long one. Rivets may also be put in where an additional thickness is brought into a joint.

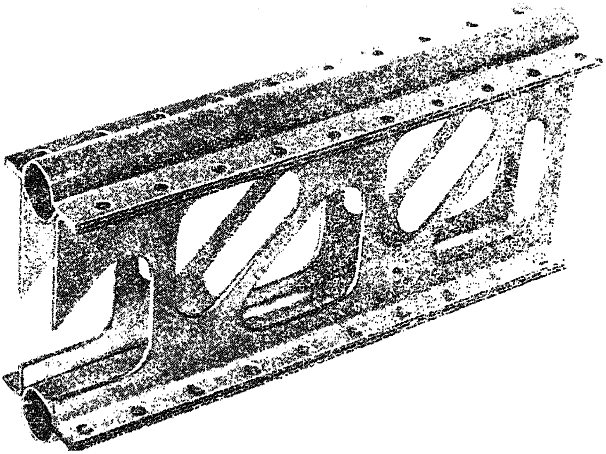

FIG. 453. DURALUMIN SPAR WELDED BY THE SCIAKY METHOD

The treble thicknesses welded are—
(i) 0·060″. (ii) 0·039″. (iii) 0·039″.
Total thickness 0·138″.

(*By courtesy of Soudeuses Electriques Sciaky, S.A.*)

Marschner goes on to suggest rules for weld spacing.

If P = spacing of welds (tolerance ± $\frac{1}{8}$ in.)
and t = average thickness of sheets
(*Note.* The ratio of thickness should not be greater than 3 : 1.)
then

(i) for secondary structures, $P = 0{\cdot}3$ in. $+ 10t$, but P should be between $\frac{1}{2}$ in. and $1\frac{1}{4}$ in.;

(ii) for primary structures, the same spacing as given by the formula for secondary structures may be used, but it should not be less than $0{\cdot}25$ in. $+ 3{\cdot}3t$;

(iii) for a lap joint, the distance from the centre line of the welds to the sheet edge should be at least $\frac{1}{8}$ in. $= 3t$;

(iv) for unflanged reinforcing or edging strips where two or more rows of welds are used, the spacing should be 1 in. per row;

(v) for other cases, where there are two or more rows of welds, the spacing should be about $1\frac{1}{2}$ times the spacing between the rows, but not less than $\frac{5}{8}$ in. nor greater than $1\frac{1}{8}$ in.

The minimum width of flange for a welded-on angle stiffener should be 0·25 in. $+ 6t$ with an absolute minimum of $\frac{3}{8}$ in. The gap of a channel section stiffener having sheet welded to the web need not exceed [illegible] in.

Other interesting suggestions are made by the same authority. Where a box-like structure or double bulkhead is being built up by attaching sheet to both flanges of a channel section, the welding may be done simultaneously on both flanges by one pair of electrodes. These are brought into contact with the opposite outer sides of the job, whilst the gap between the flanges is filled with a closely fitting block of copper, which is slid along as the welding proceeds.

In a complicated structure requiring changes in both the electrical "set-up" and the mechanical "set-up" or jigging, it is found that time and money may be saved by careful design. Changes in amperage, weld time, and pressure are easily made on the welding machine but changes in jigs are wasteful, and the design should be such that few changes or adjustments in the latter are needed.

HEAT TREATMENT OF DURALUMIN

Duralumin differs so much in its physical characteristics from the other metals in everyday use that it is not to be expected that the same methods of working may be used. The designer must recognize this and suit his details to his material.

In the normal state it is too hard and insufficiently ductile to take any shaping. Yet it is our most valuable light alloy since suitable annealing and heat treatment provide the solution to most of the difficulties. These processes are liable to be expensive and should only be called in where the design cannot be efficiently simplified. There are many cases where annealing could be dispensed with entirely.

Duralumin is usually supplied in the hard heat-treated condition, in which state it will develop its average full strength of 25 to 28 tons per square inch. For any work more intricate than the drilling of holes, simple machining, and the making of straight large radius bends, the material must be softened. It may be annealed, rendering it permanently soft, and on the completion of the work heat-treated to restore it to the normal state.

If, however, the amount of work to be done is small and can be completed within about two hours, heat treating is sufficient. Advantage is taken of its property of age hardening spontaneously at room temperatures. Immediately after heat treatment and quenching, duralumin is almost as soft as if it had been annealed. It quickly begins to harden, and at the end of a day is nearly back to normal strength. The process of hardening, however, continues at a slower rate for three or four days before the full strength is restored.

Annealing and heat treatment may be carried out in either an electrically heated air chamber or in a nitrate bath, gas heated. The latter is the more suitable for commercial practices and usual for aircraft work, but not so accurate as an electric furnace. The nitrate bath consists of a welded or riveted mild steel tank of sufficient size to take a batch of the largest sheets used. A battery of gas burners is placed along the bottom and sides of the tank below the level of the fused nitrate. Owing to the explosive properties of the nitrate when brought in contact with red-hot steel, the flame should never play on the tank side above the level of the salt. The salt used is usually an equal mixture of sodium and potassium nitrates.

A recording pyrometer must be provided, and the temperature checked against the times at which the different batches are put through. Tensile and Brinell tests on specimens should be made frequently. Immediately beside the nitrate tank must be placed a washing and quenching bath of the same size. It is convenient to have a light overhead runway with a hoist so that the hot material can be quickly transferred from one to the other. The bath should have fresh water passing through it constantly, for not only has it to quench the duralumin, but it also must wash away the nitrate, which would set up corrosion if left on. In many factories a second rinsing tank is provided in addition to the quenching tank. The water used may be either hot or cold. If hot, the nitrate dissolves more easily, but the age-hardening is accelerated.

The articles to be treated should be suspended in steel frames or baskets. They must not have contact with each other or with the sides of the tank. Annealing and heat treatment by parts is bad and should never be allowed. Each piece must be completely immersed in the nitrate. It is sometimes an advantage to hold them suspended over the hot bath for a few minutes before lowering in so that all moisture may be evaporated.

Heat treatment for temporary softening and ultimate complete restoration of strength should be carried out at a temperature of 490° C. ± 10. The periods of soaking at this temperature suggested by the Air Ministry[1] are—

Sheet and strip	Not less than	15 min
Rivets	,, ,,	15 ,,
Bar and thick sections . . .	,, ,,	30 ,,
Heavy forgings and billets . .	,, ,,	3 hr.

These times are, of course, additional to the time taken to raise the articles to the required temperature.

If the temperature is allowed to exceed 500° C., there is grave danger of burning and embrittling. The material must be quenched immediately on leaving the salt bath.

Annealing for permanent softening should be carried out at a temperature of 380° C. ± 10, and the material is not quenched, but allowed to cool off in air. The strength is reduced from 26 tons to 16 tons per square inch, and age hardening does not occur. All annealed parts must, therefore, be restored to normal strength again by heat treatment to 480° C. and quenching. Annealing must only be regarded as a method of attaining sufficient pliability to work the material extensively.

Some means of recognizing the exact state of all metal in the workshops should be adopted to distinguish between parts which have been completely heat treated and those which have only been annealed. The charge-hand or inspector on the salt bath plant should be held responsible for stamping all annealed parts as such, and only deleting that marking when returned to him for heat treatment. Without this it is exceedingly difficult for the inspection and progress departments to keep track of all units, relying solely on the word of the workmen concerned.

Finally, there are several precautions which must be taken with the nitrate bath. Potassium nitrate (saltpetre) is one of the principal constituents of gunpowder, and under certain conditions may be dangerous. Contact at a high temperature with organic matter such as wood, coke, oil, resin, etc., may result in an explosion. The nitrate must be stored in a dry place and not be put into the bath in a moist condition. In starting up a new bath the salt should be heaped on the bottom and heat applied gradually by the lower burners only. When the bath has been allowed to cool down and solidify, the reheating should be done gradually to prevent spluttering and violent cracking of the surface. Though the same salt may be used continuously over a long period, the tank should be cleaned out at intervals of a month.

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[1] *Airworthiness Handbook*, Inspection Leaflet 116.

Type of Alloy	Annealing	Solution Treatment	Quench	Ageing Treatment	Quench
Forging Alloys. Hiduminium [illegible] 59	½ to 4 hrs. 360° C.	2 hrs. 530° C.	water 70° C.	15–20 hrs. 170° C.	water or air
Duralumin RR 7[illegible], 24 S	½ to 4 hrs. 360° C.	1–3 hrs. 490°–500° C.	water	5 days natural hardening	—
Duralumin F [illegible]S.	½ to 4 hrs. 360° C.	1–3 hrs. 490°–500° C.	water	15–20 hrs. 150°–170° C.	water or air
Y alloy	½ to 4 hrs. 360° C.	2 hrs. 520° C.	boiling water	5 days natural hardening	—
	½ to 4 hrs. 360° C.	No hardening treatments.			
Casting Alloys.					
RR 50 Alumin [illegible]			—	10–20 hrs. 170° C.	water or air
		2 hrs. 510–520° C.	boiling water	5 days natural hardening	
Hiduminium		510°–525° C.	boiling water	15–20 hrs. 170° C.	water
Types of Furnace Most Efficient.					
Sheets. Extruded Bars	[illegible] Muffle.	Electric Muffle.		Electric or Gas heated.	
Forging and Stampings	Salt Bath.	Salt Bath			

In factories where much annealing is done, it is good practice to maintain a separate tank for the process. Time is not then wasted in lowering the temperature of the normalizing tank to annealing heat and then having to raise it again. It cannot be too strongly emphasized, however, that annealing should not be necessary. All parts should be so designed that the working of them may be completed in soft period following full heat treatment.

Aluminium alloy rivets are not annealed since they cannot be heat treated after hammering in position. They are heat treated, quenched, and then used during the soft period. Thus they develop their full strength on ageing. The rivets should be anodically treated before ormalizing.

The different heat treatments required by the various aluminium lloys have already been referred to in Chapter II. The table[1] on page 34 gives some useful information.

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[1] From *The Metal Industry*, 24th and 31st Jan., 7th Feb., 1936. *Light Alloy actice*, by H. G. Warrington.

CHAPTER VIII

CORROSION

Owing to the very rapid advances which are being made in the science of aeronautics, machines quickly become out of date, as not only speedier and more efficient, but also safer, craft are produced. Aircraft do not need, then, to be built to last for ever. In general engineering a corrosion margin is added to whatever scantling sizes are demanded by the strength requirement. According to J. McGovern,[1] this margin in shipbuilding amounts to as much as 10 to 15 per cent of the structure weight. It is fortunate that the aircraft designer has to make no such allowance, as an additional weight of that order would so seriously cut down the performance of his machine. Against twenty or more years of economic life in a ship we can at most set a quarter of that period for an aeroplane. To say this is not to imply that aeroplanes are like cheap cars, to be bought and scrapped at the year's end. The steps taken to counteract corrosion are rather in the form of protective coatings than in "margins" of size.

In the future, however, as the rate of scientific advance slows down and so lengthens the period over which an aircraft can be economically operated, so will the corrosion question become increasingly important. Whether it will be solved, as now, by suitable protective agents or by the use of non-corrodible steels, or even non-corrodible light alloys, remains to be seen. The possibilities of materials like "Alclad" aluminium alloy, MG7, and beryllium alloy have already been mentioned.

The effect of corrosion is to reduce the strength of the member it affects. This reduction of strength may be taken under two headings.

1. Reduction of size due to loss of material on the surface. In the simple tension case, the strength goes down in proportion to the reduction of cross section area.
2. Surface unevenness, local pitting and inter-crystalline corrosion reduce the fatigue range enormously.

The first of these is of much less importance than the second. Vibration, and consequently fatigue, occur in most of the structural members of an aeroplane. They are particularly severe in the engine mounting, the external bracing wires, and parts adjacent to these. Consequently, before the reduction of area becomes important the effect of microscopic defects on the fatigue range would have caused failure. In a high-tensile steel the fatigue range may be reduced to nearly one-half by a surface scratch one or two-thousands of an inch deep. When inter-crystalline penetration occurs the possibilities are even more serious.

Duralumin is not a metal which corrodes excessively. But, unlike steel, any corrosion which takes place is not spread in visible layers on the surface, but tends rather to concentrate in spots and to follow the intercrystalline lines inside the metal. It shows itself as a white powdery deposit on the surface. The worst corrosive agent with which the aircraft designer has to contend is, of course, salt water, particularly on marine craft. According to Dr. Aitchison,[2] the most intense corrosion of duralumin takes place in a salt solution of one-sixth the strength of sea-water. He reminds one that when material is taken out of the salt bath during the heat treatment process it should be thoroughly washed before being erected. The same authority notes the difference in resistance to corrosion between metal in the annealed condition and the final normalized and age-hardened state, the latter being the much more resistant. In fact, the difference "is sufficient to make it possible to induce galvanic effects by placing metal in the two conditions together." Pickworth[1] has noted a similar condition in the corrosion of steel where the same metal is in two or more different states of temperature, internal strain, etc., in adjacent parts, with consequent different electrical potentials. A more dangerous association is that of different metals, and it is wise to have no fittings of steel, copper or brass together with duralumin in exposed positions, in marine work.

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[1] *Trans. N.E.C. Inst. E. & S.*, Vol. XLIII, Part 7.

[2] Aircraft Engineer Supplement to *Flight*, 24th June, 1926.

Where steel must be used it should be either of one of the non-corrodible varieties or else cadmium-coated, and there should be a layer of varnished fabric inserted to separate it from other metals. Cadmium coating, the process of which is described later, has proved most satisfactory, even in flying boats and seaplanes. But it cannot be used in parts subject to friction or wear which would remove the surface. In land machines, although the use of non-corrodible steels or cadmium coating is always preferable, stove enamelling or cellulose lacquer are usually a sufficient protection for steel. There is little to choose in efficiency between these two, and in first cost the one is more expensive in time and the other in material.

Duralumin parts should always be anodically treated and coated with grease or lanoline. Chill castings in Specifications L5 or L33 do not require this treatment owing to their hard, close-grained surface. "Alclad" aluminium alloy needs only to be treated anodically when subject to powerful corrosive agents. The pure aluminium surface is electro-negative to the alloy, and therefore, when the edges are exposed or the sheet is cut or drilled, inter-granular penetration does not take place or attack the alloy centre. It is electrolytically directed to the aluminium, which is practically impervious.

Protection of Aluminium and Aluminium Alloys

Anodic Treatment. Though it is usual in other countries to protect aluminium and its alloys from corrosion by suitable paints and varnishes, an oxidation process which gives very good results has been developed in England. It is known as "Anodic Treatment," and is due to Bengough and Stuart. The patents are held by the Department of Scientific and Industrial Research. The process is an electrolytic one in which the part to be protected is made the anode. Chromic acid is used as the electrolyte. Under the influence of the current in the presence of the electrolyte we get aluminium oxide deposited as a fine adhering film on the surface of the metal.

Anodic treatment is the subject of special instructions by the Air Ministry,[2] whose inspectors must approve the plant and make periodical tests of the electrolyte, etc.

The bath itself is a welded steel tank, along the top of which run three brass tubes, one on the centre line and one towards each side. The centre tube carries the anode and the two outer ones the cathode.

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[1] *Trans. N.E.C. Inst. E. & S.*, Vol. XXXVIII, Part 7.

[2] *Airworthiness Handbook*, Inspection Leaflet No. 8.

The cathode consists of graphite plates suspended in the bath by steel wires or straps which must always be above the level of the liquid.

At the bottom of the tank is a coil through which steam or cold water may be passed to control the temperature. Some mechanical means of keeping the electrolyte in constant motion must be provided, and this may be accomplished by fitting vanes operated by an electric motor. A dial-recording thermometer must also be so fitted that it may be read by the operator.

The electrolyte is a 3 per cent solution of chromic acid in pure water, preferably distilled. The local water supply may only be used if it is certified to be free from chlorides. The chromic acid content should not fall below 2½ per cent, and losses of water should be made good from a pure supply. The composition of the electrolyte should be the subject of frequent tests.

Anodic treatment cannot satisfactorily be applied to parts already riveted or fastened together, and, as in heat treatment, each small item must be dealt with separately. If the part has been passed through annealing or normalizing processes, it must be cleaned from all traces of nitrates. In any case it should be washed in both petrol and hot water before anodizing. Parts are then hung by means of duralumin clips from the centre tube. If possible they should be totally immersed in the electrolyte, but the operation may be satisfactorily carried out in two steps with a slight overlap of the anodic surface in large sheets. Since the oxide is a non-conductor, the clips should have sharp enough points to penetrate the surface which has already been treated, if the operation is a double one. Where the size of the part makes it possible, several clips should be used in order to secure a more uniform distribution. When the parts are immersed, the electrolyte should be at a temperature of 40° C. ± 4°, and this must be maintained throughout the operation. Though it may be necessary to warm up the bath to this temperature before beginning, sufficient heat will be generated to maintain it. If the bath exceeds 44° C., cooling water should be passed through the coil at the bottom. The agitation of the electrolyte should be commenced at the beginning so that no bubbles shall form on the surface of the metal. The effect of such bubbles will be to create spots and pitting of the material.

A current of 4 amperes per square foot of surface should be employed. By surface is meant both sides of a sheet or angle. The voltage must be accurately recorded. Starting at zero, it should be increased uniformly to 40 volts in the first 15 min., and maintained at that for the next 35 min. It must then be increased to 50 volts in 5 min. and held at that for the last 5 min. An hour is thus spent on the entire process of surfacing. The parts must then be thoroughly washed in hot water to remove the chromic acid. The subsequent drying may be done in sawdust.

The anodic surface thus formed is very thin and of an almost chalky, absorbent consistency. This provides a reliable test of its quality. If an indelible pencil mark is made on it, one should not be able to wipe out the mark with a damp cloth.

Various precautions are necessary in dealing with such a strong corrosive as chromic acid. Those operating the plant should wear rubber gloves. A hood may be necessary over the tank to carry away the fumes, and the level of the electrolyte should be kept down so that spray will not jump the edge.

Further Treatment of Duralumin. Parts which are not subjected to extreme marine or corrosive influences are usually rubbed over with lanoline on top of the anodic surface. More protection is desirable for flying boat hulls and seaplane floats. After being drilled, cut to size and finished to shape, shell plates should be anodized and given one or two undercoats of oil primer before being riveted in position. A paint film will thus be formed in the seams, which may also have an insert of fabric or caulking cotton. When dry the final coats of cellulose lacquer or oil varnish may be applied. An aluminium-cellulose lacquer has been found particularly suitable for hulls, giving them some protection against even marine growths.

Where steel fittings are mounted on a duralumin hull structure a piece of fabric impregnated with bakelite varnish should be inserted between the two materials.

PROTECTION OF STEEL

Cadmium-coating. Of all the processes suggested at one time or another for the corrosion protection of steel, the electro-deposition of cadmium is now the most used in aircraft work. It lacks the high finish of chromium or nickel, but is more serviceable and does not peel. The surface which it gives is a grey "matt" one, and it is usual to finish with enamelling as an additional precaution.

In seaplane and flying boat work, where the corrosive agents are the most severe which the aircraft constructor has to face, cadmium-coating is still most useful and gives a protection almost equal in quality to stainless steel. It may well be used for internal fittings and parts removed from spray. The limitations of cadmium-coating must, however, be understood. It is only a coating and does not produce a homogeneous material. Parts, therefore, which are liable to be worn or bolt heads which may be scratched severely by a spanner should be of stainless steel in marine aircraft. In British factories the plant and materials are subject to approval and periodical inspection by the Air Ministry.

The process is carried out after all work and heat treatment of the part is completed. It must be thoroughly cleansed of rust and grease by an approved method such as sand blasting, caustic bath or scratch-brushing. Acid pickling is not suitable.

The part is made the cathode in an electrolyte consisting of cadmium and potassium cyanides dissolved in water. The anode is cast cadmium plates or rods. The current should be 10 amperes per square foot of surface to be protected and the voltage 3 to 6. The bath should be kept in circulation by methods similar to those used in the anodic treatment of duralumin in order that the coating shall be even. The current must be under close control and the process carried out not too rapidly, or the coating will be porous. The work must be completed in one dip.

The part is then removed and well washed in cold water, after which it is heated to a temperature of 100° C. to 200° C. for half an hour to remove brittleness.

When large or highly stressed parts are being treated, a test piece should be put through at the same time and tested for embrittlement.

The Air Ministry regulations[1] state that the coating must be nowhere less than 0·0003 in. thick. In bolts and similar fitted parts the increase in diameter may be of the order of 0·001 in., and where tight limits are being worked to this should be noted.

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[1] *Airworthiness Handbook*, Inspection Leaflet No. 53.

In this, as in all such similar processes, extreme cleanliness is an essential factor in successful results. The part must be clean before treatment, and all traces of the cyanides removed afterwards.

The process has been applied to components as large as a complete welded-up engine mounting in one dip.

Hot Diffusion. The hot diffusion method of protection is better known by the names of "Sherardizing" or the "D. N. Process."

The protection is given by heating the parts in a closed atmosphere in the presence of zinc oxide and finely divided zinc dust. The process lasts several hours and results in giving the steel a coating of metallic zinc which is diffused into the surface. It has a particular use for parts, which by reason of cavities, holes, etc., may not be suitable for electrolytic treatment. The coating may vary in thickness unless the work is in movement continuously, and the results are not considered to be as good as those obtained in zinc or cadmium coating process.[1] A particular form of sherardizing, known as "Freezing," is employed by Boulton & Paul, in which the thickness of the coating can be controlled within limits of ·0003 to ·0005 of an inch.

Stove Enamelling. Stove enamelling is the most popular process for the protection of steel fittings and structures. It may be applied to anything from a small fitting to a whole wing, provided that the plant is big enough, and it is frequently used on top of a cadmium coating, particularly for seaplanes.

The parts are de-scaled, preferably by pickling, though sand blasting is often used. After pickling the work must be cleaned with some evaporative solvent and oven dried. The enamel (D.T.D. 56A) is then applied by dipping, surplus enamel allowed to drain off, and the parts are stoved. The stoving promotes adhesion and dries out any lurking moisture.

Cellulose Enamels. The use of cellulose enamels (D.T.D. 63) has spread considerably in recent years. The result may not be quite as satisfactory as that given by stove enamel, but it is simple and quick. It further allows a wide range of pigments. The usual method of application is spraying. Brushing or dipping may be used. An undercoating is usually given to improve adhesion on steel or on the anodically treated exterior surfaces of duralumin hulls and floats. It is important that the work be degreased, particularly as no heat, which might dry it, is employed. Any moisture or traces of rust, scale, etc., will prevent the enamel "taking" on the true surface of the metal, and though a covering film may form it will not adhere long in service. Cellulose enamels are made under various trade names, and in cases of difficulty the manufacturers may be called upon to advise.

Treatment of Exhaust Manifolds, etc. A great deal of difficulty has been found in protecting exhaust pipes and manifolds owing to the combination of heat and corroding media.

Experiments have been made[2] with high-chromium stainless steel for this purpose, but it has not proved equal to a low-carbon steel protected by such methods as fescolizing, calorizing, aluminium spraying or dipping.

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[1] See *Journ. R.Ae.S.*, January, 1932, "Protection of Metal Parts of Aircraft Against Corrosion," Sutton.

[2] *Ibid.*

Fescolizing is a process for the electro-deposition of nickel.

Calorizing is similar in principle to Sherardizing, but the powder used is a mixture of aluminium dust, alumina, and ammonium chloride. As a high temperature, 680° C., is used, the method should only be applied to such steels as will be unaffected by this heat. A layer of aluminium is deposited which merges into and alloys with the steel, forming a satisfactory non-scaling surface. The dipping and spraying processes have also been tried.

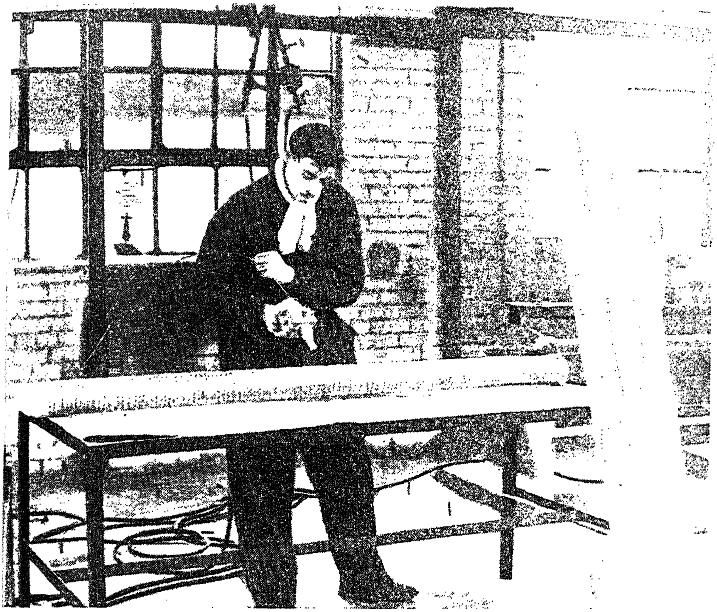


FIG. 454. METAL SPRAYING PROCESS

(By courtesy of "Aircraft Production" and Metal Sprayers Ltd.)

Metal Spraying. The metal spraying process has developed considerably in recent years and is now approved for certain types of aircraft work under Air Ministry D.T.D. Specifications Nos. 906 and 907.

The purpose of the process is to deposit a coating of metal on the surface of some article which itself may be metal or wood, fabric, etc. Any metal may be used for spraying which can be provided in wire form, or which may melt in an oxy-hydrogen flame. The metal to be sprayed is fed in the form of a wire through a pistol in which it is melted and atomized.

Fig. 454 shows the process in use and the form of the pistol may be seen clearly.

The wire may be from 1 to 2 mm. diameter, the larger size being used when the metal has a low melting-point. It is fed through the pistol automatically at a speed appropriate to its melting-point and the work in hand. As the wire passes into the pistol it is melted in a blow lamp flame, round which is a cone of compressed air fed through another lead.

This atomizes the molten metal as it leaves the nozzle and throws it out in a very fine spray at high velocity. The air rapidly absorbs the heat from the atomized metal so that it is only slightly warm by the time it is 4 in. away from the nozzle.

The pistol is held so that the spray impinges at right angles on the surface which has to be coated.

This surface must have been thoroughly cleaned and be absolutely free from scale or grease. The Air Ministry requires that it shall be prepared by blasting with steel grit, and the operators handling the cleansed surface must wear rubber gloves. The spraying must be done a few minutes after the blasting. One great advantage of this process is that it can be applied to articles of any dimensions free from the restriction of sizes of baths, stoves, and so forth. There is no heat distortion in the process, and it can, therefore, be applied to thin walled components.

A special form of metal spraying known as "aluminizing" is used for exhaust pipes and other parts subjected to high temperatures. An aluminium coating is sprayed on to the component and it is then covered with a bituminous paint followed by heat treatment in a muffle furnace at 800° C. The effect is to alloy the inner layers of the aluminium with the steel, and form a solution of the one in the other. The outer layer consists of a thin coating of aluminium oxide. When the whole of the component has been raised to 800° C. it is removed from the furnace and allowed to cool. If the shape of the part is such as to cause distortion, it should be mounted in a jig whilst cooling. Afterwards it is brushed with steel wire brushes giving the surface an even silvery appearance. The thickness of the coating, according to Air Ministry requirements, should be uniform, and not less than 0·007 in.

PROTECTION OF MAGNESIUM AND MAGNESIUM ALLOYS

Chromating Process. The surface must first be prepared. Parts which have been machined to fine limits should be boiled for ½ hr. in 2 per cent caustic soda solution. Parts which have not been machined to fine limits should be dipped for a quarter of a minute in 10 per cent nitric acid and washed. The final machining may then be carried out and the work immersed in 2 per cent caustic soda solution.

The chromating process which follows this preparation consists of gently boiling the parts for 6 hours in a solution made as follows. Highly concentrated solutions of potassium alum and caustic soda are mixed. To this is added a concentrated solution of potassium dichromate so that the final strength is—

Potassium alum .	1 per cent
Caustic soda .	½ ,,
Potassium dichromate	1½ ,,
Water . . .	the rest.

Losses by evaporation on boiling should be made good.

A film is formed which should be further protected by two under coatings of metal primer followed by a coat of cellulose lacquer all sprayed on. Six hours should be allowed for drying between the coats of primer and then 4 hours before the final lacquering.

This process is satisfactory for aeroplanes operating under dry conditions, but magnesium alloys should not be used for marine aircraft.

Selenium Process. The Selenium Process, developed by Bengough and Whitby at the Chemical Research Laboratory, Teddington, gives a surface protection to elektron alloys. It makes an excellent base for paint and should perhaps be regarded in that light.

For the alloys covered by D.T.D. Specifications 59A, 88B, 127A, the parts should be cleaned and immersed for 5 min. at room temperature in a solution of 10 per cent selenium dioxide in water containing 0·5 per cent sodium chloride. D.T.D. 136A should be immersed for 15 min. The parts should then be well washed and dried at 100° C. or with porous material.

For the alloys covered by D.T.D. Specifications 118, 140, and 142, the parts after cleaning should be immersed for 15 min. in an aqueous solution of 2 per cent sodium selenite, containing 6 c.c.s of orthophosphoric acid per litre at ordinary room temperature. After treatment the parts are removed and allowed to drain until dry, which leaves a smooth reddish brown film.

An alternative treatment for D.T.D. 118, 140, and 142 is as follows. The parts are immersed for 30 sec. in a 1 per cent solution of chromic acid at 90° C.; washed and immersed in a 10 per cent aqueous selenium dioxide solution at room temperature for 30 to 60 sec. Before applying paint, all traces of soluble matter must be washed from the film, and it must be thoroughly dry. It is recommended that a priming coat of zinc chromate pigmented tung oil-base paint be used, followed by a top coat of aluminium pigmented cellulose lacquer.

These processes for the protection of elektron are all patented and the advice of Messrs. F. A. Hughes & Co., Ltd., Abbey House, Baker Street, London, N.W.1, should be sought.

FRETTAGE CORROSION

While the corrosion which has so far been considered in this chapter has been associated with atmospheric effects, there is another form of corrosion which occurs between tight fitting metal parts. This is known as frettage corrosion and is in no way connected with external conditions. The parts may be completely dry or even coated with oil or grease, but after a time, if made of steel, they show a rust-coloured dust, or mud if oil is present. This form of corrosion only occurs when one of the parts is of metal and when there is vibration. The vibration causes a very slight movement between the parts, even though they are tight fitting. Hard and stainless steels appear to be more subject to the trouble than soft materials, and brass is particularly subject to it if in association with steel.

This is now being investigated systematically at the National Physical Laboratory, but no final report has so far been issued. Whilst it is a trouble which is more likely to occur on aero engines it has been found in certain parts of the airframe and airscrew, particularly where ball bearings have been used under conditions of vibration.

CHAPTER IX

RIVETING

Solid Rivets. Rivets provide one of the best methods of fastening two parts together permanently. They will, however, only carry their load in shear. Any tension on the heads tends to burst them apart, loading them in a way they are ill-fitted to stand.

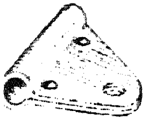


FIG. 455

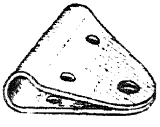


FIG. 456

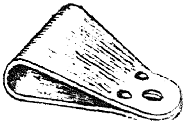


FIG. 457

Fig. 455 shows a use of rivets which is bad. Under strain, the shackle will only be prevented from opening by the stiffness of the material and by pulling against the rivet heads. The result may be as illustrated in Fig. 456. Had the shackle been designed as in Fig. 457, though not perfect, it would have been much better, and its tendency to straighten out would have been less. This simple and perhaps painfully obvious example serves as an introduction. The more complicated cases of rivet head tension, caused, perhaps, by drumming or vibration of a structure, may not become so obvious until failure occurs, but the possibility should always be present in the designer's mind.

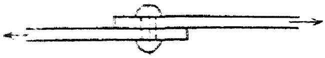


FIG. 458

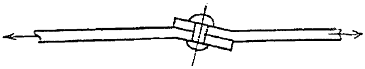


FIG. 459

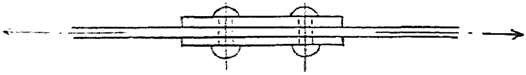


FIG. 460

A further example is in the popular single lap (see Fig. 458), which tends to alter to the form shown in Fig. 459. Here the number of rivets, as in a flying boat hull seam, may be sufficient to ensure that the tension on each is minute. The double strap form of joint completely removes the possibility (Fig. 460). Many types and shapes of rivets are known to engineering, from the square-headed tap rivet to the big taper-shank pan head rivet. The two in most common use on aircraft structures are the snap-head (Fig. 461) and the countersunk (Figs. 462 and 463). The snap-head is made in all sizes from $\frac{1}{16}$ in.

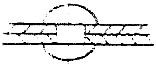


FIG. 461

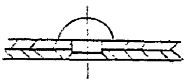


FIG. 462

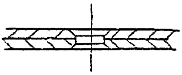
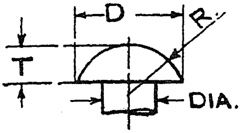


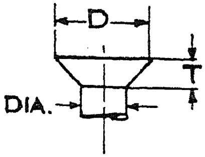
FIG. 463

diameter upwards, but the countersunk rivet cannot be used in plates of less than 20 s.w.g., and consequently it is not found in general practice below $\frac{1}{8}$ in. diameter.

The standard sizes of heads and the length of shank which must be allowed for forming them are here tabulated.

TABLE I



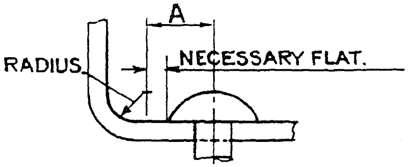


Diameter	SNAP-HEAD				COUNTERSUNK HEAD		
	D	T	R	Length to form Head	D	T	Length to form Head
in.	in.	in.	in.	in.	in.	in.	in.
$\frac{1}{16}$	0·11	0·04	0·06	0·09	0·10	0·03	0·03
$\frac{3}{32}$	0·16	0·06	0·09	0·12	0·15	0·04	0·05
$\frac{1}{8}$	0·22	0·08	0·12	0·16	0·20	0·05	0·06
$\frac{5}{32}$	0·27	0·09	0·15	0·19	0·25	0·06	0·08
$\frac{3}{16}$	0·32	0·11	0·17	0·23	0·30	0·08	0·09
$\frac{1}{4}$	0·44	0·15	0·23	0·31	0·40	0·10	0·13
$\frac{5}{16}$	0·55	0·19	0·29	0·39	0·50	0·13	0·16
$\frac{3}{8}$	0·65	0·22	0·35	0·47	0·60	0·15	0·19

The "Length to form Head" is, of course, the length of shank standing proud of the plate surface when the rivet is inserted in its hole. The total length of rivet required is this dimension plus the thickness of material through which it passes.

The forming and holding-up tools require a certain space bigger than the head diameter, and when the rivet is used close to the flange of an angle allowance must be made. Table II gives average allowances, but the conditions vary according to the type of tool used.

TABLE II



Rivet Shank Diameter	Dimension "A"
in.	in.
$\frac{1}{16}$	0·13
$\frac{3}{32}$	0·17
$\frac{1}{8}$	0·21
$\frac{5}{32}$	0·24
$\frac{3}{16}$	0·28
$\frac{1}{4}$	0·36
$\frac{5}{16}$	0·44
$\frac{3}{8}$	0·53

RIVET STRENGTHS

The shear strength of a rivet is given by its cross-sectional area of shank multiplied by the maximum permissible shear stress of the material—i.e.

$$\pi \times d^2 \times f_s.$$

Its bearing strength in a plate is given by the thickness of plate t multiplied by the diameter of shank d and the maximum permissible bearing stress of the material—i.e. $t \times d \times f_b$.

Assuming that both rivet and plate are of the same or similar materials we get a relation between these two strengths such that if made equal —i.e.

$$\frac{\pi \times d^2}{4} \times f_s = t \times d \times f_b$$

—the collapse will be simultaneous. This gives us the most economical size of rivet for any given thickness of plate. In duralumin, taking

$$f_s = 16 \text{ tons per sq. in.}$$

$$\text{and } f_b = 32 \quad ,, \quad ,,$$

$$\frac{\pi \times d^2 \times 16}{4} = t \times d \times 32$$

$$12{\cdot}56\, d^2 = 32\, td$$

$$12{\cdot}56\, d = 32\, t$$

$$d = 2{\cdot}55\, t.$$

Similarly in mild steel, where

$$f_s = 18 \text{ tons per sq. in.}$$

$$\text{and } f_b = 38 \quad ,, \quad ,,$$

$$\text{we get } \underline{\underline{d = 2{\cdot}69\, t.}}$$

In stainless steel rivets (D.T.D. 161.)

$$\underline{\underline{d = 3{\cdot}19\, t,}}$$

and in high-tensile steel

$$d = 3{\cdot}18\, t.$$

From this it appears that the most economical size of rivet is approximately three times the thickness of the plate through which it passes. This ideal condition cannot be observed in practice, particularly where several different thicknesses are used in making up a part or fitting. The appropriate sizes may be tabulated as follows—

TABLE III

Thickness of Plate	Diameter of Rivet	
	Aluminium Alloy and Mild Steel	Stainless and High Tensile Steel
	in.	in.
22 s.w.g.	$\frac{1}{16}$	$\frac{3}{32}$
20 ,,	$\frac{3}{32}$	$\frac{1}{8}$
18 ,,	$\frac{1}{8}$	$\frac{5}{32}$
16 ,,	$\frac{5}{32}$	$\frac{7}{32}$
14 ,,	$\frac{7}{32}$	$\frac{1}{4}$
12 ,,	$\frac{1}{4}$	$\frac{5}{16}$
10 ,,	$\frac{5}{16}$	$\frac{7}{16}$

It will be noticed that thicknesses below 22 s.w.g. have not been considered. Tests have shown[1] that the relationship breaks down. This is an important point, as a very considerable amount of aircraft riveting is done in structures such as strip steel spars, which are frequently in thicknesses down to 28 s.w.g. Radcliffe is led to the conclusion that the bearing strength of the rivet need not be considered in these cases, the criteria of strength being the shear value of the rivet and the bearing and buckling values of the plate. This being so, he concludes that rivets in single shear are more efficient than those in double shear. He tabulates a number of tests on both single and double shear joints, which may be of assistance to designers. Until more data are in existence, the strengths of riveted joints in thin materials should be made the subject of tests in all critical cases. Buckling of the material round the rivet is a factor which defies calculation, as it varies according to the local conditions.

The following Strength Tables give the values of the most usual rivet sizes in plate thicknesses from 22 s.w.g. to 8 s.w.g. Extreme cases, such as $\frac{1}{16}$ in. diameter rivet in 10 s.w.g. and $\frac{1}{4}$ in. diameter rivet in 22 s.w.g., have been missed as unlikely to occur in practice.

In fittings where only one or two rivets are used, these figures should be reduced by 30 per cent.

TABLE IV. SINGLE SHEAR STRENGTHS

Note. For double shear multiply these values by 2.

Diameter	Cross Section Area	Aluminium Alloy, L37 $f_s = 35{,}850$ lb./sq. in.	Mild Steel and Stainless Steel, D.T.D. 161 $f_s = 40{,}320$ lb./sq. in.	High Tensile Steel $f_s = 74{,}000$ lb./sq. in.
in.	sq. in.	lb.	lb.	lb.
$\frac{1}{16}$	0·0031	111	125	230
$\frac{3}{32}$	0·0069	247	278	510
$\frac{1}{8}$	0·0123	441	495	910
$\frac{5}{32}$	0·0192	689	775	1,420
$\frac{3}{16}$	0·0276	990	1,112	2,040
$\frac{1}{4}$	0·0491	1,760	1,975	3,630
$\frac{5}{16}$	0·0767	2,750	3,090	5,670
$\frac{3}{8}$	0·1104	3,960	4,450	8,175

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[1] See *Journal R.Ae.S.*, November, 1930, Radcliffe, p. 954.

Bearing Strengths of Rivets in Plates above 0.022 in. (24 s.w.g.)

TABLE V. ALUMINIUM ALLOY, SPEC. L.3

f_b = 70,000 lb./sq. in.

Diam. of Rivet	22 s.w.g. 0·028 in.	20 s.w.g. 0·036 in.	18 s.w.g. 0·048 in.	16 s.w.g. 0·064 in.	14 s.w.g. 0·080 in.	12 s.w.g. 0·104 in.	10 s.w.g. 0·128 in.	8 s.w.g. 0·160 in.
$\frac{1}{16}$	122	157	210		Greater than double shear			
$\frac{3}{32}$	183	236	315	420		values of aluminium		
$\frac{1}{8}$	245	315	420	560	700		alloy rivets	
$\frac{5}{32}$	307	395	525	700	875	1,137		
$\frac{3}{16}$	368	474	630	840	1,050	1,365	1,682	
$\frac{1}{4}$	—	630	840	1,120	1,400	1,820	2,240	2,800
$\frac{5}{16}$	—		1,050	1,400	1,750	2,275	2,800	3,500
$\frac{3}{8}$	—			1,660	2,100	2,730	3,360	4,200

TABLE VI. MILD STEEL (S3) AND STAINLESS STEEL (S85)

f_b = 100,000 lb.

Diam. of Rivet	22 s.w.g. 0·028 in.	20 s.w.g. 0·036 in.	18 s.w.g. 0·048 in.	16 s.w.g. 0·064 in.	14 s.w.g. 0·080 in.	12 s.w.g. 0·104 in.	10 s.w.g. 0·128 in.	8 s.w.g. 0·160 in.
$\frac{1}{16}$	175	225			Greater than double shear			
$\frac{3}{32}$	262	337	450			values of M.S. and		
$\frac{1}{8}$	350	450	600	800	1,000		S.S. rivets	
$\frac{5}{32}$	438	563	750	1,000	1,250			
$\frac{3}{16}$	525	676	900	1,200	1,500	1,950		
$\frac{1}{4}$	—	900	1,200	1,600	2,000	2,600	3,200	4,000
$\frac{5}{16}$	—	—	1,500	2,000	2,500	3,250	4,000	5,000
$\frac{3}{8}$	—	—	—	2,400	3,000	3,900	4,800	6,000

TABLE VII. 5 PER CENT NICKEL STEEL SHEET (S4)

f_b = 161,000 lb.

Diam. of Rivet	22 s.w.g. 0·028 in.	20 s.w.g. 0·036 in.	18 s.w.g. 0·048 in.	16 s.w.g. 0·064 in.	14 s.w.g. 0·080 in.	12 s.w.g. 0·104 in.	10 s.w.g. 0·128 in.	8 s.w.g. 0·160 in.
$\frac{1}{16}$	282	362	484		Greater than double shear			
$\frac{3}{32}$	421	543	725	965		values of H.T.		
$\frac{1}{8}$	563	724	965	1,287	1,610		rivets	
$\frac{5}{32}$	705	906	1,208	1,610	2,015	2,620		
$\frac{3}{16}$	845	1,089	1,450	1,930	2,415	3,140	3,865	
$\frac{1}{4}$	—	1,448	1,930	2,580	3,220	4,180	5,150	6,440
$\frac{5}{16}$	—	—	2,415	3,220	4,025	5,230	6,440	8,050
$\frac{3}{8}$	—	—		3,860	4,830	6,280	7.730	9,660

These are the most usual materials for aircraft fittings. Parts ma o other specifications may be interpolated. Stainless steel sheet pecification D.T.D. 60 B. is stronger than the material of S.S. rive o Specification D.T.D. 161. Table VI should, therefore, be used.

Design of Joints. The design of riveted joints is simple and is giv n most textbooks on Applied Mechanics.

The method of stressing a joint where the loading is eccentric is o frequently explained, yet such joints are very usu tructures. (Students should consult *Strength of Materials*, J. Case 932, p. 68, for a full treatment.)[1]

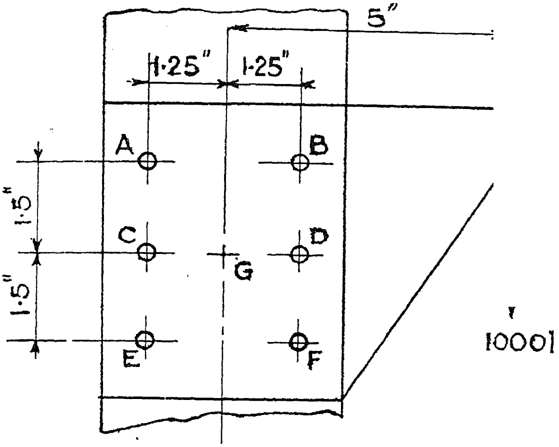

FIG. 464

Imagine a riveted fitting resisting a load of 1000 lb. acting eccen rically on the fitting.

Then each rivet is under the action of two shearing forces.

1. Direct and equal to $\dfrac{1000}{\text{No. of rivets}} = 167$ lb.

2. Resisting the turning moment, 1000 × 5 lb. in. where 5 in. is the erpendicular distance between the line of the load and the centroid f the group of rivet holes. The fitting will tend to turn about this oint, and each rivet will resist the turning moment by a force propor ional to its distance from the centroid.

The total load on any rivet is the vector sum of 1 and 2. The cen roid will be seen by inspection of Fig. 464 to lie at the position marked . The distance, y, of G from the rivets A, B, E, and F is 1·95 in. nd the distance of C and D is 1·25 in.

To find the shearing force on any rivet due to this turning moment, ivide the moment by the sum of the distance squared of each rivet rom G and multiply by the distance of the particular rivet considered rom G, i.e.

Shearing Force due to turning moment on rivet A

$$= \frac{M}{\Sigma y^2} \times y_a$$

---

[1] See also "Practical Aircraft Stress Analysis," D. R. Adams (Pitman).

where
$$M = 1000 \text{ lb.} \times 5 \text{ in.}$$
$$\Sigma y^2 = (4 \times 1{\cdot}95^2) + (2 \times 1{\cdot}25^2)$$
$$= 18{\cdot}375 \text{ in.}^2$$
$$y_a = 1{\cdot}95 \text{ in.}$$

Since rivets *A*, *B*, *E*, and *F* are all the same distance from *G*, this gives the same result in each case,

$$= \frac{5000 \times 1{\cdot}95}{18{\cdot}375}$$
$$= 532 \text{ lb.}$$

Similarly the Shearing Force due to Turning Moment on rivets *C* and *D*

$$= \frac{5000 \times 1{\cdot}25}{18{\cdot}375}$$
$$= 340 \text{ lb. each.}$$

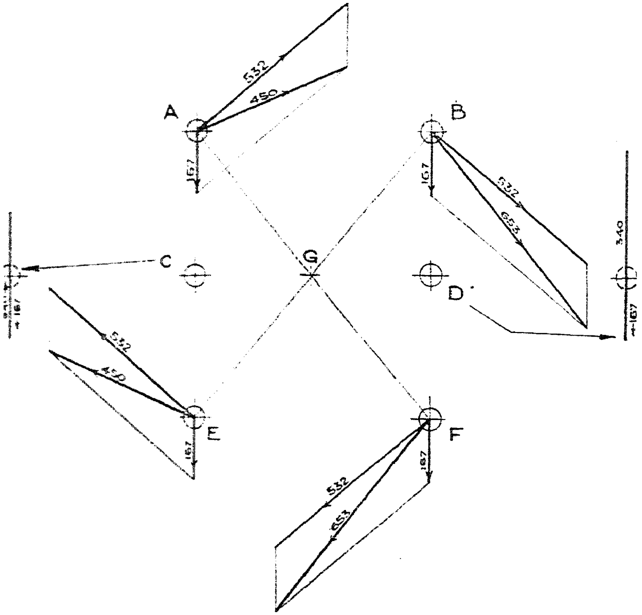

FIG. 465

The loads act at right angles to the lines joining the rivet centres to *G*, respectively. The moment-resisting load on each rivet is then combined with the direct load, acting parallel to the line of action of the applied load, in a parallelogram of forces, as shown in Fig. 465.

The resultant loads on the rivets are—

Rivets *A* and *E*	450 lb.
Rivets *B* and *F*	653 lb.
Rivet *C*	173 lb.
Rivet *D*	507 lb.

In the above method, the resultant load on each rivet must be worked out to find which is the most heavily-loaded. A simplification of the method (due to Professor W. G. Sutton, *Journal of the Institution of*

Structural Engineers, Sept. 1933) allows the resultant load on the most heavily-loaded rivet to be found at once. The loads due to the moment act at right angles to the lines joining each rivet to the centroid, G. The resultant loads, represented by the diagonals of the parallelograms, act at right angles to lines joining each rivet to a point O. This lies on a line passing through G, normal to the line of the applied load and on the side of G remote from it.

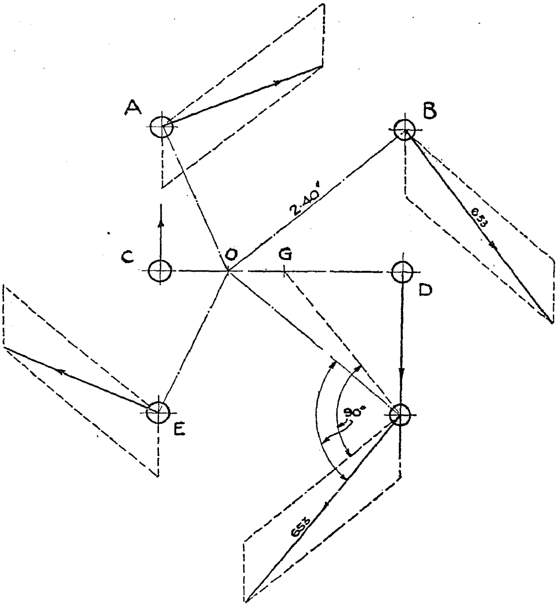

FIG. 466

$$\text{The distance } OG = \frac{\Sigma y^2}{Nl}$$

Where Σy^2 = the sum of the squares of the distances of the rivets from G.

N = No. of rivets.

l = eccentricity of applied load.

hen the most highly-stressed rivet is the one farthest from O, and the resultant total load is $\frac{Wl}{\Sigma y^2}$ multiplied by the distance of the rivet from O, where W is the externally applied load.

Repeating the above numerical example—

$$OG \quad \frac{18{\cdot}375}{6 \times 5} = {\cdot}6125 \text{ in.}$$

$$\frac{Wl}{\Sigma y^2} = \frac{1000 \times 5}{18{\cdot}375} = 272.$$

The rivets *B* and *F* are the most distant from *O*, and the distance scales 2·40 in. The total resultant load on these is, therefore—

653 lb.

It will be seen that this method is much quicker and the result accurate.

Spacing of Rivets. In flying boat and seaplane work, keel and keelson butts and laps should be treble riveted, whilst shell plate edges, floor plates and frame web laps should be double. In monocoque fuselages, single riveting is usual. When speaking of double and treble riveting it is assumed that "chain riveting" is meant. "Reeled" riveting is confined to the flanges of angles, channel stiffeners, etc., where the width of material cramps the pitching. The definitions of the above terms will be clear from Fig. 467.

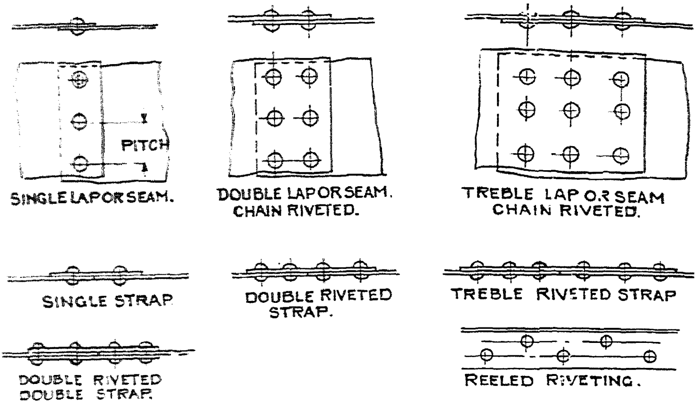

FIG. 467

In a small fitting or clip the question of spacing the rivets will be decided by the design of the detail as a whole. In general, however, it may be said that no rivet should be nearer the edge of a plate than twice its diameter, and the minimum distance between rivets should be three diameters.

In metal spars, fuselages and seaplane floats and hulls, general rules may be laid down to cover most cases. In the long lines of rivets used in these structures a spacing of eight diameters is usual except where watertightness is necessary. For hulls and floats a pitch of four diameters should be used in all shell seams, attachments of frames and stringers to the shell, and such important structural members as keel and keelson butts, floor plates, etc.

The above ruling of two diameters between centre of rivet and edge of plate should be observed, and where double and treble lines of rivets are used, a spacing of three diameters should be allowed between centres of lines.

Where single straps are used on one side of the joint only, they are made of material of the same thickness as the parts they join, or of one gauge thicker. Double straps, one on each side of the joint, are made of the next size above half the thickness of the parts they join.

For large scale riveting, such as that on flying boat hulls, Table III of appropriate diameters for given thicknesses of material may be simplified, and is given here together with lap and strap widths, in accordance with the rules just stated.

TABLE VIII

Thickness of Plating	Diameter of Rivet	Width of Lap			Width of Strap		
		Single	Double	Treble	Single	Double	Treble
	in.	in.	in.	in.	in.	in.	in.
14	$\frac{3}{16}$	0·75	1·35	1·90	1·50	2·65	3·75
16	$\frac{5}{32}$	0·65	1·10	1·50	1·25	2·20	3·15
18-20	$\frac{1}{8}$	0·50	0·90	1·25	1	1·75	2·50

Precautions and Workshop Practice. The effect of hammering up a rivet head is felt not only on the head itself, but also on the plate immediately round the rivet. At each point the plate is stretched very slightly. In long rows this stretching becomes quite appreciable, and sufficient to cause "wind" in a spar or built-up strut. On a hull or fuselage it will cockle the plate along the length of the lap. The trouble can be prevented. A spar should be bolted up with service bolts at every fourth hole along all its flanges before the first rivet is put in. A washer should be put on each side of the plate to protect the anodic film. The rivets should then be inserted in the intermediate holes, starting from the ends and middle simultaneously in all flanges. Similarly, in a hull or fuselage the plate should be bolted in position at every fourth hole, and the riveting should not "grow" round the edge from one point alone. The more it is spread about within practical limits, the better. If the lap is arranged near a longitudinal stringer, the stiffness of this will prevent undue cockling and the resultant drumming of the plate. A similar precaution is to swage the plate edges (Fig. 468). Where corrugated sheet is used, this, of course, occurs automatically.

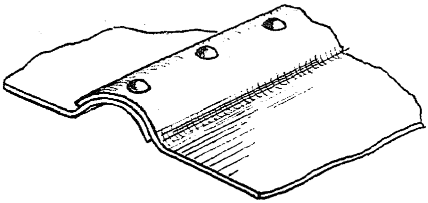

FIG. 468

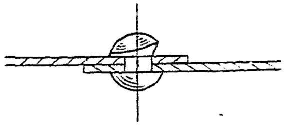

FIG. 469

The question of badly-formed rivet heads is frequently raised by inspectors, who are countered by "knowing" foremen claiming that since rivets are only used in shear the head shape is immaterial. Whilst this is to some extent true, it does not go the whole way. A half-formed head (Fig. 469) indicates that inefficient or insufficient hammering has been applied to it, with the result that the shank of the rivet is not properly expanded and pressed home into its hole.[1]

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[1] See *Airworthiness Handbook*, A.P.1208, Inspection Leaflet 24, for inspection of riveting.

Hand riveting is expensive and often unsatisfactory. There is more possibility of damage to the surrounding plate, and the heads are frequently poor. Pneumatic riveting is satisfactory when carefully carried out. The tool is of the kind used in shipyards for light caulking. But the best workmanship is obtained from a single pressure tool.

The saving in time which is given by the use of a pneumatic riveter is shown in Fig. 470. This diagram, which is developed from Pleines' paper on riveting methods in the *Journal of the Royal Aeronautical Society*, September, 1938, is the result of a systematic comparison made in Germany. It shows that the time required for pneumatic riveting is only a fraction of that required for hand riveting. Since the cost of riveting is very considerable particularly with modern forms of stressed skin construction this saving is most important.

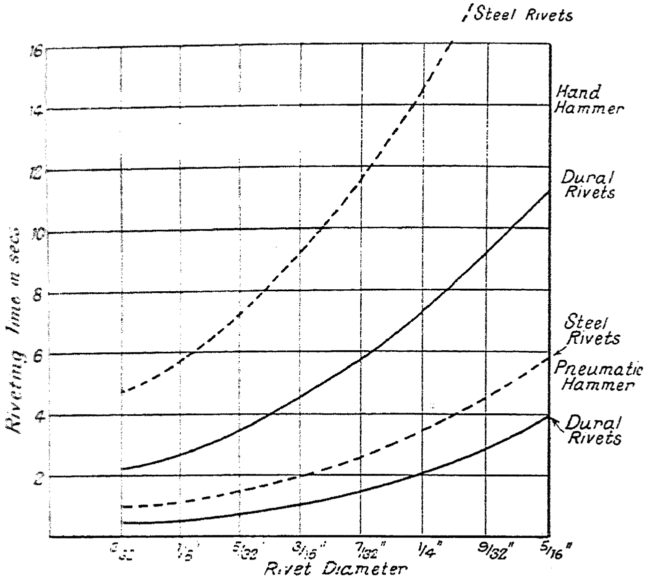

FIG. 470. COMPARISON OF PNEUMATIC AND HAND RIVETING TIMES

Pleines points out that where pneumatic riveting is used, the weight of the hammer is most important. The proportion of percussive power of the hammer to the size of the dolly must be right for the diameter of the rivet. It is uneconomic to use light pneumatic hammers giving a large number of blows for driving heavy rivets, as they tend to peen the head without upsetting the shank. Consequently the shank end undergoes a local increase in hardness causing cracks in the head, and later shearing of the head in quite low static loads. Pleines suggests that the time taken in seconds to form the head should be less than the diameter of the rivet in millimetres; in English units this means that the time in seconds should be little more than the diameter of the rivet in $\frac{1}{32}$nd of an inch, using multiblow pneumatic hammers. He further suggests that the dolly for driving duralumin rivets should not be less than 0·06 to 0·075 k.g. per mm. sq. of the rivet shank section area (85–100 lb. per sq. in. of rivet shank section area).

The dolly should, of course, be heavier than this if possible, and the weight should be concentrated as near as possible to the rivet head. This is illustrated in Fig. 471.

Internally sprung dollies are used in Germany particularly for flush riveting of thin plates. They allow a much shorter striking time and facilitate safe handling of the tool because the vibrations set up are concentrated in the interior of the dolly (see Fig 472). Where crank dollies have to be used owing to inaccessible rivet heads they must be made much heavier than the minimum weight for straight dollies.

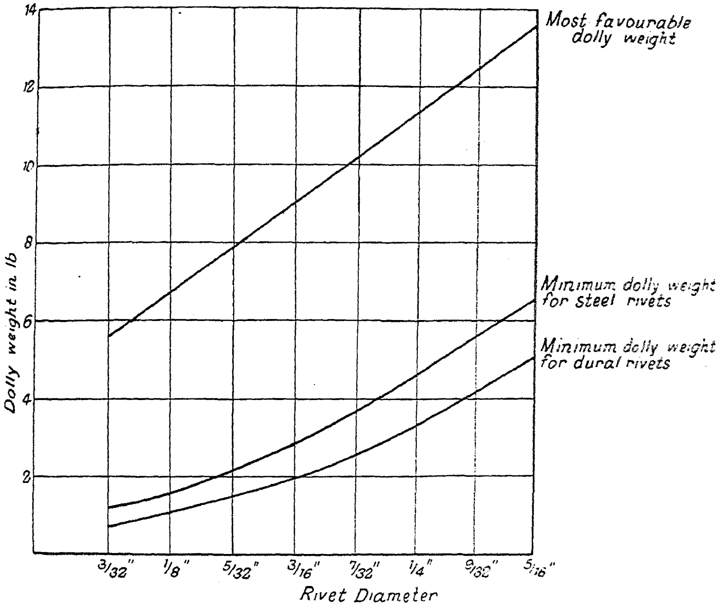

FIG. 471. RIVETING DOLLY WEIGHTS

Single shot riveters have become increasingly popular particularly for the larger sizes of rivet. They are quieter and quicker in their action and produce a more satisfactory rivet in that the shank is properly extended and the head not merely burred over.

Aluminium alloy rivets should not be used in the annealed condition. Not only will they never develop their full strength, but they are liable to induce corrosion in the surrounding plate. The usual procedure is to coat them anodically first and to follow this by full heat treatment to 490° C. ± 10, and quenching. If used within an hour they are soft and pliable, and will age-harden to their full strength later.

This age hardening can be interrupted or retarded for many hours if the rivets are kept in cold storage. Freshly quenched rivets may be kept in a workable condition for 24 hours if stored in refrigerators at a temperature of — 2° C. When they are removed from the refrigerator, the limit of driving period is the same as if they had been just quenched. One precaution which must be observed is that the rivets

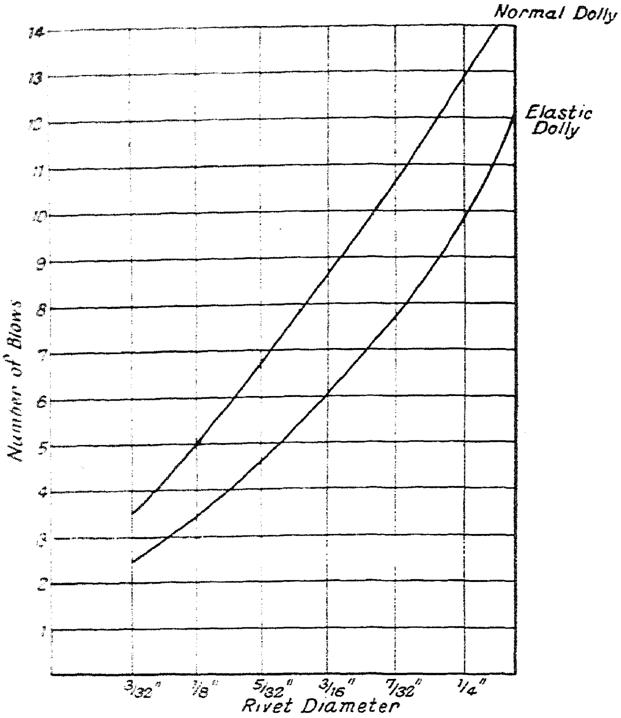

FIG. 472

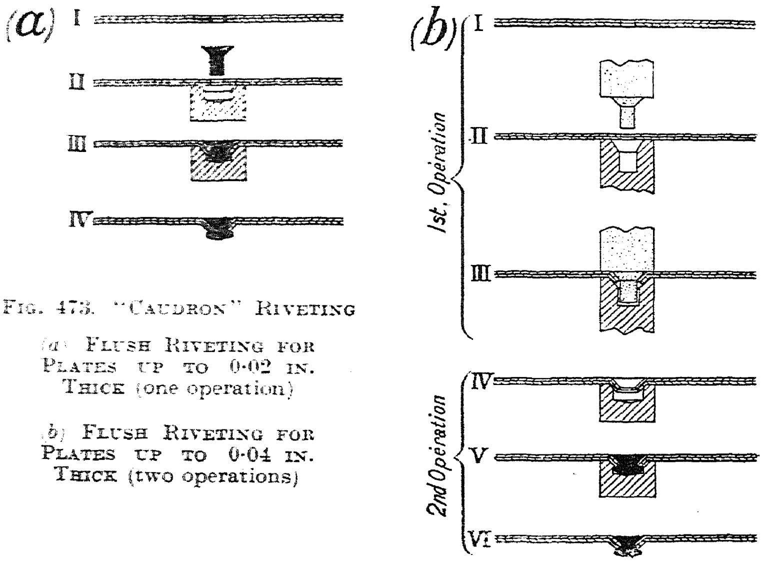
(a)
I
II
III
IV
(b)
I
II
III
1st. Operation
IV
V
VI
2nd Operation

FIG. 473. "CAUDRON" RIVETING

(a) FLUSH RIVETING FOR PLATES UP TO 0·02 IN. THICK (one operation)

(b) FLUSH RIVETING FOR PLATES UP TO 0·04 IN. THICK (two operations)

(*By courtesy of "L'Aéronautique"*)

are quite dry when driving. If they are coated with a thin layer of this will set up corrosion subsequently in the riveting hole.

It is argued that in hull and seaplane work the rivet heads are the corrosion danger-points, particularly as the hammered-up ends cannot have an anodic surface. A method[1] of overcoming this fault which is employed by Messrs. Saunders-Roe, Ltd., is to hammer up on the inside of the hull, at least up to the waterline. This is only possible on hulls with an extremely accessible internal structure, and there are some points where it cannot be done. The principle may be applied in riveting together panels of shell plating before erection.

Where the obstruction to the air flow, caused by the rivets, may be comparatively small on large machines, it becomes of importance on small, fast craft. In such aeroplanes the skin is usually too thin to allow of countersinking, but when it is supported inside by a robust member, this may be countersunk and the skin forced down into the hollow, making, in effect, a countersink on the outer surface. A method of flush riveting thin sheet, used by Caudron, is illustrated in Fig. 473.

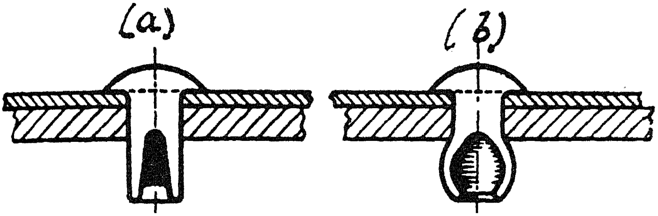

FIG. 474. HEINKEL EXPLOSIVE RIVET

(By courtesy of the Royal Aeronautical Society)

A is a method applied to plates up to ·02 in. thick. The metal is pierced to the diameter of the rivet. A dolly, with a countersunk cavity, is held inside and the rivet inserted from outside. In hammering up, the head is formed and the material bent inwards at the same time. *B* shows the method applied to plates up to ·04 in. thick, where the work is done in two portions. The hole is pierced as before, and the material round the hole forced back by a special tool. This is withdrawn, the rivet inserted and hammered up against a dolly inside. In both cases the outside finish is completely flush. (*Cf.* De Bergue rivet, p. 335.) This type of riveting is widely used in France.

Heinkel Explosive Riveting. The explosive rivets developed in Germany by Heinkel solve one of the great problems in riveting, that is, of connecting two parts where one side is completely inaccessible. The explosive rivets before and after use are illustrated in Fig. 474.

The shank of the rivet is made hollow, and filled with a small quantity of explosive which is protected from moisture by a coat of varnish. The explosive is non-corrosive in itself and the fumes subsequently formed are equally safe. A heated tool (see Fig. 475) is held against the rivet head until a temperature of 120° C. is built up. The rivet then explodes and takes the form shown above. The time taken is only a matter of two seconds, and, of course, an assistant holding the dolly is not required. It would be shorter if a higher temperature were used, but there would be some risk of affecting the material surrounding the rivet. In order to prevent this the rivet itself is covered with a thin coating of insulating varinsh.

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[1] See *Airworthiness Handbook*, A.P. 1208, Inspection Leaflet 43.

In general the rules governing the use of explosive rivets are similar to those for normal riveting. The holes must be drilled to the exact size, and the parts must be clamped together with clamping screws.

Tubular Rivets. Tubular rivets are extensively used in thin metal strip structures, solid rivets not being particularly satisfactory in material below 22 s.w.g. in thickness. The ordinary relationship between shear and bearing strengths breaks down and failure occurs, due to buckling of the thin metal round the rivet. Undoubtedly the clamping effect of the rivet head helps in some small degree, but the theoretically perfect joint of equal strength against all types of failure is not attained. The tubular rivet has a higher efficiency in thin sheet, since for a given shear strength its outside diameter is greater than that of the solid rivet. The bearing area is, therefore, greater and the bearing stress less for the same load.

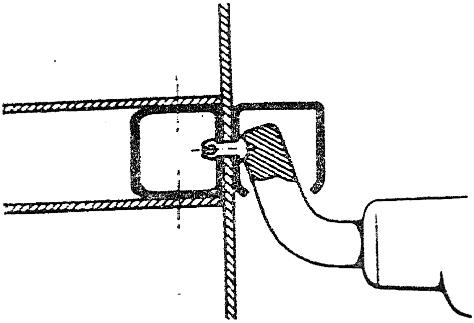


FIG. 475. TYPICAL USE OF HEINKEL EXPLOSIVE RIVET

(By courtesy of the Royal Aeronautical Society)

Tubular rivets are not, however, 100 per cent efficient in shear, as will be realized by considering one with a large outside diameter and an extremely thin shell. If this D/t ratio is too large, the shell will collapse before shearing. The shear and bearing strengths of tubular rivets are not, then, calculable, and failure takes the form of secondary collapse or buckling. Designers must rely largely on tests in their stress estimates. Very few test results have been published, and they could only be used with full knowledge of the circumstances. For preliminary calculations before testing or when an approximation only is needed, an efficiency of 50 per cent is frequently assumed. This will serve as a rough guide within the range of sizes normally fitted, where D/t ratio is about 6, and t, the thickness of the rivet shell, from 1 to $1\frac{1}{2}$ times the thickness of the sheet. This gives

$$\text{Shear strength} = \frac{\pi(D^2 - d^2)}{4} \times 0{\cdot}5 f_s$$

$$= 0{\cdot}39\,(D^2 - d^2)\,f_s,$$

where f_s = maximum permissible shear stress,

D = outside diameter,

d = inside diameter.

The full stress may be assumed in bearing, giving

Bearing strength $= D \times T \times f_b$,
where $T =$ thickness of sheet joined,
$f_b =$ maximum permissible bearing stress.

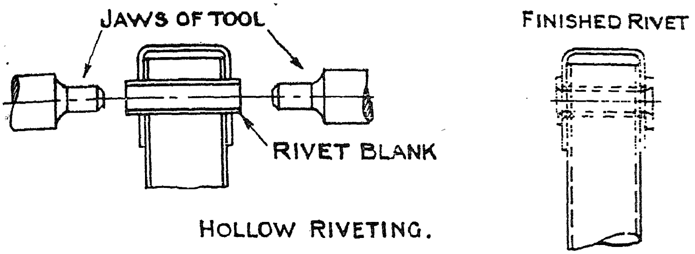


FIG. 476

The rule that rivets must not be used where there is any tension tending to bend the head applies with even more force to tubular rivets than to solid ones. The holding power of the head is negligible.

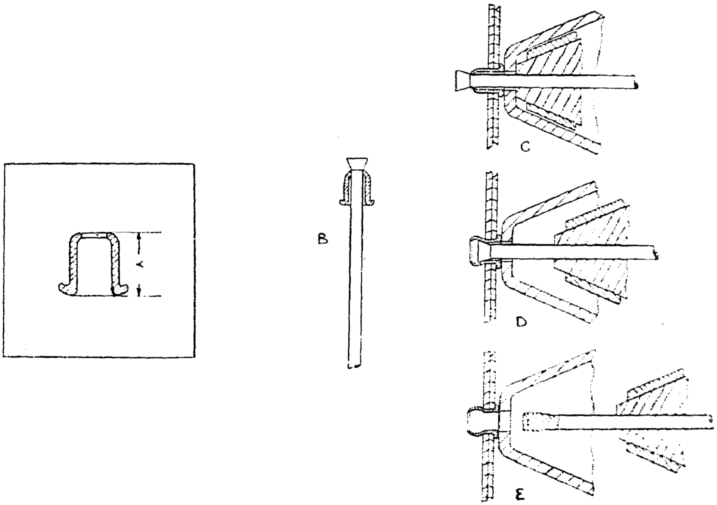


FIG. 477. POP RIVETING

The fitting of tubular rivets is simple, and may be accomplished either by squeezing or spinning. The form of the tools used is indicated in Fig. 476. For small work in duralumin or mild steel, a hand-operated squeezer on the scissor principle is adequate. In spinning the shape of the tool end is similar, but the shank is gripped in the chuck of a drill. It is advisable to have a tapered entry followed by a short parallel spigot of slightly larger diameter than the bore of the rivet to expand it fully into the hole.

In the example shown, which is the attachment of a cross-bracing tube into the channel boom of a rib, care would have to be taken not to damage the channel by too much squeezing. In repetition work the tool may be designed to meet in the middle, as a precaution.

Tubular rivets for thin strip structures are used in sizes from ¼ in. to ⅛ in. outside diameter and in thicknesses from 20 s.w.g. down to 26 s.w.g. They may be made from tube of any specification, but the most usual are in duralumin (T4), and mild steel (T35). High-tensile and stainless steel rivets are made in materials appropriate to the strip they join.

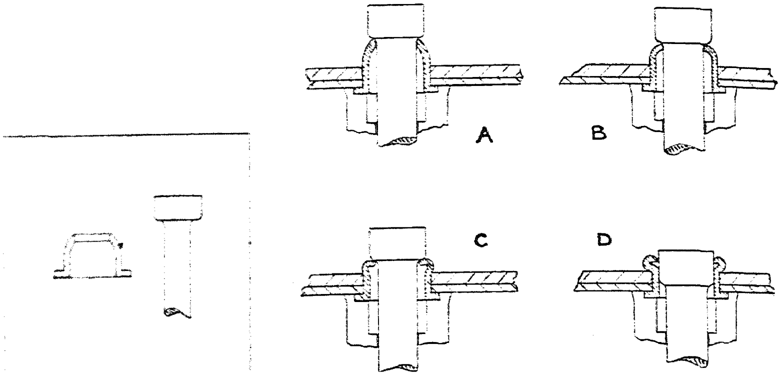


FIG. 478. LARGE DIAMETER POP RIVETING

Some very ingenious methods of tubular or "pop" riveting have been devised by the A.T.S. Co., Ltd., which, under Major Wylie, combines the patented processes for metal construction of the Armstrong-Whitworth, Boulton & Paul, and Gloster firms. These methods are particularly applicable to riveted joints which are inaccessible on one side, and in which the rivet head cannot be supported by a dolly during the closing. Examples of such uses are found in the attachment of ribs and fittings to tubular spars, or of sheet covering to floats and monocoques.

A tubular rivet threaded on to a mandrel is inserted in the hole from outside. Whilst the rivet is held in position the mandrel is withdrawn, expanding the rivet and forming a rim on the inside. In the case of small rivets up to $\frac{3}{16}$ in. diameter the mandrel is only used once, and then, since it is deformed by the work it does, discarded. An example in which a ⅛ in. diameter rivet is used is shown in Fig. 477. The rivet is pressed out of sheet steel. It has a thickness of ·018 in, and the length *A* is ·21 in. This is suitable for a total thickness of joint up to about ·12 in. The mandrel consists of a length of 15 s.w.g. steel wire with a head tapered up to ·105 in. in a length of ·07 in. The rivet is threaded on to the mandrel *B*, put into the tool and inserted in the hole *C*. The mandrel is withdrawn whilst the nose of the tool holds up the rivet (*D*). At first the taper on the mandrel merely forms a rim at the inside end of rivet, but as it is completely withdrawn (*E*) it expands the rivet completely into the hole and is, at the same time, drawn down in size itself to about ·015 in. The mandrel is then thrown away.

In the second form of "pop" riveting, over $\frac{3}{16}$ in. diameter, the mandrel is made from steel, Specification S.28, hardened to over 100 tons per sq. in., and it is not destroyed by the process. In the example (Fig. 478) the rivet is $\frac{5}{16}$ in. outside diameter and ·032 in. thick. The head of the mandrel is ·005 in. bigger than the inside bore of the rivet and the stem is ·15 in. diameter. The steps of the process are shown and it will be realized that more force is required than in the first method. A hand tool for dealing with rivets up to $\frac{3}{16}$ in. diameter is shown in Fig. 479, from which it will be seen the same pressure which holds up the rivet head withdraws the mandrel. A foot-operated tool has been developed for the larger sizes.

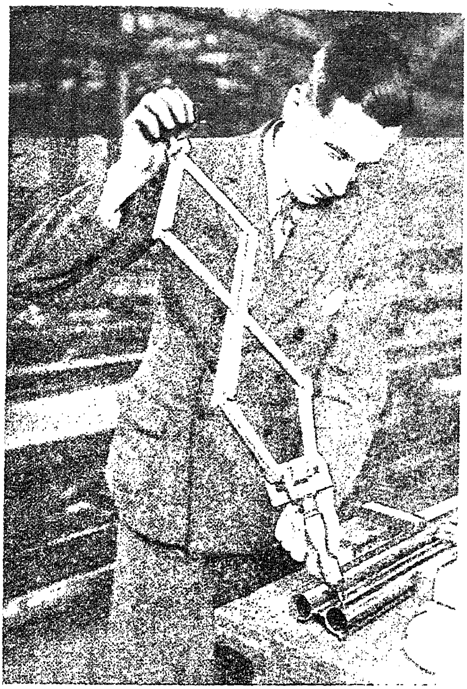
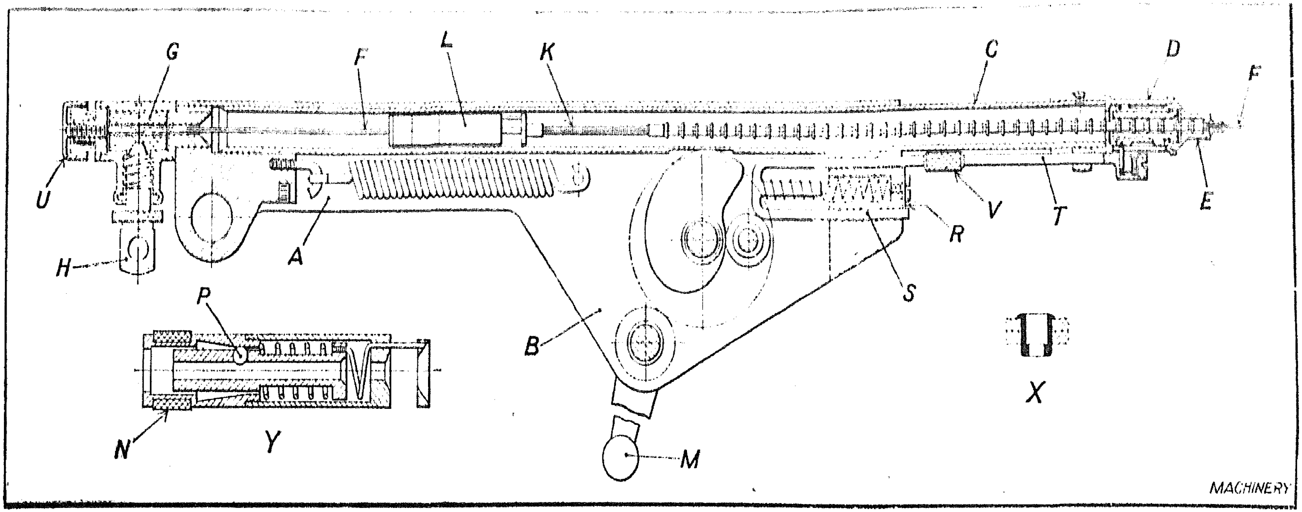


FIG. 479. POP RIVETING TOOL

Rivets of this kind have shown themselves to be at least equal in tensile strength to solid snap-head rivets. This may be due to the very tight fit of the rivet in the hole. In vibration they have proved equally satisfactory. In shear a strength of not less than 240 lb. may be expected from the $\frac{1}{8}$ in. rivet shown in Fig. 477.

There are several developments of the "pop" rivet. They may be used with shear bushes of the type described on page 212. Where watertightness is required, a soft steel sealing cup is pressed into the rivet and spun out to close the hole.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MACHINERY

FIG. 480. PART-SECTIONED VIEW OF THE CHOBERT GUN

The inset on the left shows an enlarged view of the slide which feeds the rivets towards the mandrel, and on the right is a detail of the actual finished rivet

(*By courtesy of "Machinery"*)

Another system of riveting which has been developed in France by Chobert and in England by Aviation Developments, Ltd., is similar to the "pop" riveting already described. The rivets are hollow and are expanded by drawing a tapered mandrel through them. With this system, however, up to one hundred rivets are threaded on to a single mandrel which is put into a hand operated machine, or "gun," shown in Fig. 480. One rivet on the mandrel projects from the muzzle of the gun and is inserted through the rivet hole. The gun is pressed hard up against the work, perpendicular to it, and the handle is turned three times. This causes the rivet to be expanded in the hole by withdrawing the tapered end of the mandrel through it and prepares the machine for the next one. The manufacturers estimate that on straightforward work a continuous production speed of 1,200 rivets an hour is possible.

CHAPTER X

TABLES OF SPECIFICATIONS AND STRENGTHS OF MATERIALS

Specifications, B.E.S.A. and D.T.D. with Strength Values.

Uses of Materials. Bolt Strengths

Specification and Strength of Materials

In the following tables are listed most of the standard materials used in metal aircraft construction. The ultimate tensile strengths, yield points, proof stresses and chemical compositions are as stated in the specifications. The maximum permissible shear and bearing stresses are arbitrary, being based largely on experience, and hence may be subject for criticism. Each designer used his own values for these, and there is considerable variation. Many of the figures here are given by kind permission of the Royal Aeronautical Society and Mr. F. Radcliffe, B.Sc.[1]

The chemical composition of a material is not of direct interest to the designer, except in as far as he avoids mixing, for example, steel and duralumin without anti-corrosion protection. These figures are stated for the purpose of identifying and comparing materials, particularly by overseas readers, to whom the British specifications mean nothing.

Abbreviations—

f_t = Ultimate tensile stress.
f_y = Yield point.
f_p = Proof stress, occurring at that point on the stress-strain diagram where the curve departs by 0·1 per cent of the original gauge length from the straight line of proportionality.
f_s = Maximum permissible shear stress.
f_b = Maximum permissible bearing stress.

$$E \div 10^6 = \frac{\text{Modulus of elasticity}}{1{,}000{,}000}$$

$\ngtr$ = Not greater than.
$\nless$ = Not less than.
Al = Aluminium.
C = Carbon.
Ce = Cerium.
Cr = Chromium.
Cu = Copper.
Fe = Iron.
Mn = Manganese.
Mo = Molybdenum.
Ni = Nickel.
P = Phosphorus.
Pb = Lead.
Mg = Magnesium.
Si = Silicon.
S = Sulphur.
Ti = Titanium.
Va = Vanadium.
W = Tungsten.
Zn = Zinc.

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[1] Radcliffe, "Elements of Detail Design," *Journal R.Ae.S.*, November, 1930.

e materials are arranged in the following order—

Steels and Alloy Steels :

(1) Bars, Rods, Wires, etc.
(2) Non-corrodible Bars, Rods, Wires, etc.
(3) Sheet and Strip.
(4) Non-corrodible Sheet and Strip.
(5) Tubes.
(6) Non-corrodible Tubes.

Light Alloys :

(1) Aluminium Alloy Bars, Forgings, etc.
(2) Aluminium Alloy Sheet and Strip.
(3) Aluminium Alloy Castings.
(4) Aluminium Alloy Tubes.
(5) Magnesium Alloy Bars, Forgings, etc.
(6) Magnesium Alloy Sheet and Strip.
(7) Magnesium Alloy Castings.
Nickel Copper Alloys.

USES OF MATERIALS

(Short List of most generally used Materials)

STEELS AND ALLOY STEELS

(1) STEEL BARS, RODS, FORGINGS, ETC.

Specification	Uses
3 S1 . .	MILD STEEL BAR. Bolts and nuts, machined fittings, eyebolts, tube plug ends and sockets, etc., on commercial and civil aircraft, particularly where low stresses are used. May be welded if heat treated afterwards. If heat treatment is not possible by reason of the size of the unit, S21 should be used instead. *Protective treatment :* Cadmium coating, with stove enamel or cellulose lacquer.
2 S2 . . S65 . .	55 TON ALLOY STEEL BARS. 65 TON NI-CR. STEEL BARS AND FORGINGS. High tensile bolts and nuts, machined fittings, eyebolts, tube plug ends and sockets for highly stressed parts, particularly in association with T50 tubing in fuselage members, interplane and drag struts, engine mountings, undercarriages, and tail skids; and in association with built-up members of high tensile strip, such as [illegible]. High finish is required. Tool marks and sharp edges must be removed. *Protective treatment :* Cadmium coating, with stove enamel or cellulose lacquer.
3 S6, 2 S76 .	"40" CARBON STEEL BAR. Forgings and stampings. Should not be welded unless heat treated afterwards. S76 is a heat treated version of S6 to give higher tensile strength. *Protective treatment :* Cadmium coating, with stove enamel or cellulose lacquer.
2 S21 . .	LOW CARBON STEEL BAR. Rivets. Machined fittings, tube plug ends and sockets, etc., if over 1¼ in. diameter and welded, when heat treatment is not possible. Suitable for case hardening. *Protective treatment :* Cadmium coating with stove enamel or cellulose lacquer.
D.T.D. 126A .	40 TON CARBON STEEL.

Non-corrodible Steel Bars, Rods, Forgings, etc.

Specification	Uses
1 S11 . .	55–65 Ton Nickel Chromium Steel Bars, Forgings, etc.
2 S2[illegible] . .	Air-hardening Nickel-chrome Steel Bars, Forgings, etc.
S61 . .	High Chromium Steel Bars, Forgings, etc. (Stainless Iron). Low tensile strength for purposes similar to S1. Not completely stainless. Must not be used in contact with Austenitic "18–8" Stainless Steel. *Protective treatment :* Stove enamel or cellulose lacquer.
S62 . .	High Chromium Steel Bars, Forgings, etc. (Modified Stainless Iron). For purposes similar to S61, but with higher carbon content and greater strength. Not completely stainless. Must not be used in contact with Austenitic "18–8" Stainless Steel. *Protective treatment :* Stove enamel or cellulose lacquer.
S[illegible] . .	3½ per cent Nickel Steel Bars, Forgings, etc.
S80 . .	High Chromium Steel Bar, Forgings, etc. ("18–2" Group). Machined and forged fittings, eyebolts, tube plug ends, and sockets for highly stressed parts, especially in marine work, and in association with high tensile non-corrodible tube, D.T.D. 105. For parts similar to those made in S2, where good corrosion resistance is required. *Protective treatment :* Varnish or cellulose lacquer if for marine purposes.
2 S[illegible] . .	65–75 Ton Nickel Chromium Steel Bars, Forgings, etc.
D.T.D. 161 .	Rivets, split pins, etc. May work harden.
D.T.D. 176A .	Steel Bar (Austenitic "18–8" Group). Machined fittings where high resistance to corrosion is required. Work hardening. May be welded but stainless properties are slightly affected. Has medium tensile strength and low proof stress. Must not be used in contact with Stainless Iron. *Protective treatment :* Varnish or cellulose lacquer, if for marine purposes.

(3) Steel Sheet and Strip

Specification	Uses
3 S3 . .	Hot Rolled Mild Steel Sheet. For all ordinary sheet metal fittings, wiring lugs, etc., on commercial and civil aircraft, particularly if welding is used. Need not be normalised after welding if impracticable. *Protective treatment :* Cadmium coating with stove enamel or cellulose lacquer. Cadmium must not be used on built-up fittings where traces of the plating solution might penetrate between laminations.
3 S4 . . . S[illegible]6 . . .	5 per cent Nickel Steel Sheets. High Tensile Ni-Cr. Steel Sheets. High tensile sheet metal fittings, wiring lugs, etc., in structure of built-up strip such as S88, and with tubular structures of T50. High finish is required. Tool marks and sharp edges must be removed. Heat treatment requires accurate control, particularly with 3 S4, when a test piece from each batch must be included. *Protective treatment :* Cadmium coating with stove enamel or cellulose lacquer.
S88 . . . S87 . . .	High Tensile Ni-Cr. Steel Strip. Ni-Cr. Steel Strip, Hardened and Tempered. Built-up structures, main plane spars, closed or riveted joint tubing for struts, fuselage members, etc. May be rolled or drawn in either hard or annealed condition. *Protective treatment :* Stove enamel or cellulose lacquer.

(4) NON-CORRODIBLE SHEET AND STRIP

Specification	Uses
S85 . . . D.T.D. 30 .	STEEL SHEET (Stainless Iron). LOW TENSILE STEEL SHEET (Stainless Iron). Ordinary sheet-metal fittings, similar to S8, where stress is low. May be welded if heat treated afterwards. Not completely stainless. Must not be used in contact with Austenitic "18–8" Stainless Steel. *Protective treatment:* Stove enamel, varnish, or cellulose lacquer.
D.T.D. 46A .	HIGH TENSILE STEEL STRIP (Modified Stainless Iron). Strip for built-up structures where high tensile properties similar to those of S87 and S88 are required. May be rolled or drawn in either hard or annealed condition. Must not be used in contact with Austenitic "18–8" Stainless Steel. *Protective treatment* (if any): Stove enamel, varnish, or cellulose lacquer.
D.T.D. 60B .	STEEL SHEET AND STRIP. ("18–2" Group.) Strip for built-up structures where better stainless qualities than D.T.D. 46A are required. Sheet for hull and seaplane fittings, used preferably where little bending is needed. Also fittings, wiring lugs etc., for main planes, monocoques, and built-up strip fuselages of N.C. steel strip. May be welded but accurate heat treatment is required. Is now being used experimentally in work assembled by electric spot welding. *Protective treatment* (if any): Stove enamel, varnish, or cellulose lacquer.
D.T.D. 146A .	HIGH CHROMIUM STEEL SHEET AND STRIP. ("18–2" Group.) Similar to D.T.D. 60A but with lower tensile strength.
D.T.D. 166A .	STEEL SHEET AND STRIP. (Austenitic "18–8" Group.) Strip for built-up structures, main plane spars, drawn strip tubes for struts and fuselage members where high resistance to corrosion is required. Sheet for fittings on hulls and seaplanes, monocoque fuselages, etc. May be edge or spot welded, but strength at weld reduced to that of D.T.D. 171A. Is now being used experimentally in work assembled by electric spot welding. Work hardens, but may be softened by heat treatment. Must not be used in contact with Stainless Iron. *Protective treatment* (if any): Stove enamel, varnish, or cellulose lacquer.
D.T.D. 171A .	STEEL SHEET AND STRIP. (Austenitic "18–8" Group.) Medium tensile strength with low proof stress. High stainless qualities. Fittings for hulls and seaplanes, monocoque fuselages, etc., where low stresses are allowable. May be welded and used without subsequent heat treatment. Work hardens, but may be softened by heat treatment. Must not be used in contact with Stainless Iron. *Protective treatment* (if any): Stove enamel, varnish, or cellulose lacquer.

(5) STEEL TUBES

Specification	Uses
2 T1	35 TON CARBON STEEL TUBE. Euler struts where no welding is required. If T1 must be welded it requires heat treatment. (T1 is now replaced by T35 and T45 for general purposes in many factories.) *Protective treatment:* Cadmium coating, if possible, stove enamel or cellulose lacquer. Oiled internally.
2 T2	NICKEL CHROME AXLE TUBE. Axles and such parts where great strength and toughness are required. Must not be welded, soldered, or subject to heating of any kind. Preferably should be finished complete to shape and size with all holes etc., by the tube manufacturers. *Protective treatment:* Cellulose lacquer or paint. Oiled internally.
2 T26	MILD STEEL TUBE. Small, lightly loaded parts, such as trailing edges, equipment frames, fairing supports, and other secondary structure, tubular rivets. May be welded. *Protective treatment:* Cadmium coating if possible, with stove enamel or cellulose lacquer.
T35 T45	CARBON STEEL TUBE. DITTO. For all general purposes, particularly when welded: fuselages, engine mountings, welded tail units, etc. Does not require heat treatment after welding, but strength is reduced in the vicinity of the weld. T35 refers to special sections, streamline, oval, and round up to ½ in diameter. T45 refers to round tubes of ½ in. diameter and over. *Protective treatment:* Cadmium coating if possible, with stove enamel or cellulose lacquer, etc. Oiled internally.
T50	HIGH TENSILE CARBON STEEL TUBE. Must not be welded or brazed. Tubular fuselages with mechanical joints, interplane and drag struts etc. *Protective treatment:* Stove enamel or cellulose lacquer. Oiled internally.
D.T.D. 107	45 TON STEEL TUBE. For interplane and drag struts, undercarriages and other tubular structures mechanically jointed.
D.T.D. 254	75 TON NICKEL CHROMIUM STEEL TUBES. For interplane and drag struts, undercarriages, and other tubular structures mechanically jointed.

(6) NON-CORRODIBLE STEEL TUBES

Specification	Uses
D.T.D. 97A D.T.D. 102A D.T.D. 203A	LOW TENSILE TUBE. (Stainless Iron.) 35 TON STEEL TUBE. (Stainless Iron.) 50 TON STEEL TUBE. (Stainless Iron.) These stainless iron tubes are the equivalent of the following specifications and may be used for similar purposes, where non-corrodible properties are desirable, e.g. in flying boats and seaplanes. D.T.D. 97A equivalent to T21 ,, 102A ,, T1 ,, 203A ,, T50 They may be welded but must be heat treated afterwards. The strengths of these tubes are developed by heat treatment. Must not be used in contact with Austenitic "18–8" Stainless Steel. *Protective treatment (if any):* Stove enamel, varnish, or cellulose lacquer.
D.T.D. 199	50 TON HIGH CHROMIUM NON-CORRODIBLE STEEL TUBES.
D.T.D. 207	35 TON CHROMIUM-NICKEL NON-CORRODIBLE STEEL TUBES.
D.T.D. 211	50 TON CHROMIUM-NICKEL NON-CORRODIBLE STEEL TUBES.

LIGHT ALLOYS

(1) ALUMINIUM ALLOY BARS, FORGINGS, ETC.

Specification	Uses
5 L1 . . L39 . .	DURALUMIN BAR. For lightly stressed fittings where rigidity is required. Machined fittings and packing blocks for flying boat hulls, floats, [illegible] duralumin wing structures, etc. Bolts where lightly loaded. *Protective treatment:* Anodic, with lanoline, varnish, or cellulose lacquer.
L36 . . .	ALUMINIUM RIVETS. Used on all aluminium structures. *Protective treatment:* According to component. If this is anodically treated it must be done in parts before riveting.
L37 . . .	DURALUMIN RIVETS. Used on all duralumin and alclad structures. *Protective treatment:* Anodic before normalizing. Lanoline, varnish, or cellulose lacquer, according to rest of component, which must be anodically treated in parts before riveting.
L40 . . .	ALUMINIUM ALLOY FORGINGS. For forgings, stampings, etc., used on production work instead of 4 L1 machined fittings. *Protective treatment:* Anodic, with lanoline, varnish, or cellulose lacquer.

(2) ALUMINIUM ALLOY SHEET AND STRIP

Specification	Uses
4 L3 . . L38 . .	DURALUMIN SHEET. ALCLAD SHEET. For flying boat hulls, floats, monocoque fuselages, main plane spars, ribs, tail units, etc. May also be used for lightly-stressed plate fittings. Alclad is superior to duralumin in corrosion resisting properties, and is especially used for marine work. *Protective treatment:* Anodic, followed by lanoline, varnish, or cellulose lacquer. If used in riveted components, the parts must be anodically treated before riveting.
2 L4 . 2 L16 . .	HARD ALUMINIUM SHEET. HALF-HARD ALUMINIUM SHEET. For tanks, engine cowlings, wheel "spats," and fairings. L4 may be used for very lightly-stressed equipment fittings, straps for fuel pipes and pitot tubing, etc. *Protective treatment:* Anodic on exposed parts, varnish paint, or cellulosc lacquer.
D.T.D. 177A . D.T.D. 182A .	7 PER CENT MAGNESIUM-ALUMINIUM ALLOY SHEET AND STRIP. (Hard.) 7 PER CENT MAGNESIUM-ALUMINIUM ALLOY SHEET AND STRIP. (Annealed.) Similar in strength to duralumin but lighter. May be welded. Known commercially as M.G.7. *Protective treatment* (if any): Anodic, and/or varnish or cellulose lacquer.

(3) ALUMINIUM ALLOY CASTINGS

Specification	Uses
3 L5 . . L33 . .	CASTING ALLOY (Al–Zn). CASTING ALLOY (Al-Si). For cast packing blocks, aluminium tank fittings, control wheels, etc. May be welded to aluminium. *Protective treatment:* As for components on which used.
L35 . .	"Y" ALLOY CASTINGS.
D.T.D. 309 . . D.T.D. 255 . .	ALUMINIUM ALLOY CASTING (Hiduminium R.R. 53C). ALUMINIUM ALLOY CASTING (Ceralumin C). For light castings where high strength is required. Should be X-rayed. *Protective treatment:* Anodic, with lanoline, varnish, or cellulose lacquer.

(4) ALUMINIUM ALLOY TUBES

Specification	Uses
4 T 4 .	DURALUMIN TUBES. For fuselage structures with mechanical joints, torque tubes, and control connecting rods, control columns, tail unit and aileron spars taking torsion. In small sizes for tubular ribs. Tubular rivets when lightly stressed and tubular distance pieces in duralumin spars, etc. *Protective treatment:* Anodic, followed by lanoline, varnish or cellulose lacquer.
4 T 9 . .	ALUMINIUM TUBES. For petrol and oil systems, breather pipes, secondary structure where very lightly loaded, fairing stringers, equipment supports, and seats. May be welded. *Protective treatment:* Anodic on exposed parts. Varnish, paint, or cellulose lacquer.
D.T.D. 220A .	ALUMINIUM ALLOY TUBES. As for 4T4 but having greater strength at the same weight.

(5) MAGNESIUM ALLOY BARS, FORGINGS, ETC.

Specification	Uses
D.T.D. 88B .	MAGNESIUM ALLOY FORGINGS, STAMPINGS, PRESSINGS. Forgings, etc., for small non-stressed parts, equipment fittings, etc. *Protective treatment:* Chromate or Selenium process, with cellulose lacquer, enamel, or varnish.
D.T.D. 259 .	MAGNESIUM ALLOY BARS. Extruded sections for window frames, door steps, equipment fittings, etc. *Protective treatment:* Chromate or Selenium process, with cellulose lacquer, enamel, or varnish.
D.T.D. 142 .	MAGNESIUM ALLOY BARS. Extruded sections as for D.T.D. 259. Machined fittings for tanks, etc. May be welded. *Protective treatment:* Chromate or Selenium process, with cellulose lacquer, enamel, or varnish.
D.T.D. 184 .	MAGNESIUM ALLOY BARS.

(6) MAGNESIUM ALLOY SHEET AND STRIP

Specification	Uses
D.T.D. 118 .	MAGNESIUM ALLOY SHEETS. Tanks, cowling, seats, fairings, and equipment fittings. Suitable for welding. *Protective treatment:* Chromate or Selenium process with cellulose lacquer, enamel, or varnish.

(7) MAGNESIUM ALLOY CASTINGS

Specification	Uses
D.T.D. 140A .	MAGNESIUM ALLOY CASTINGS. Control wheels, landing wheels, equipment fittings, packing blocks, distance pieces, etc. *Protective treatment:* Chromate or Selenium process, with cellulose lacquer, enamel, or varnish.

NICKLE-COPPER ALLOYS

Specification	Uses
D.T.D. 204 .	MONEL METAL. Structural parts near compasses. Float and hull structures. *Protective treatment:* Cellulose lacquer, enamel or varnish.
D.T.D. 308 .	INCONEL. Exhaust manifolds. *Protective treatment;* none.

Specification No.	Material	Strength Values (Tons/sq. in.)					Lb./sq.
		f_t	f_y	f_p	f_s	f_b	E/10⁶
2 T1	35-Ton Carbon Steel Tube	35	30	29	24	52	28
2 T2	Nickel-chrome Axle Tube	85	—	75 (0·2%p)	47	127·5	29
2 T26	Mild Steel Tube .	[illegible]	—	11 (0·2%p)	12	30	30
T35	Carbon Steel Tube .	35 30*	—	30 25* (0·2%p)	23 18*	52 45*	27·4
T45	Carbon Steel Tube .	45 30*	—	25* (0·2%p)	26·5 22·5*	67·5 45*	28·8
T50	50-Ton Nickel Steel Tube	50	—	45 (0·2%p)	30	75	28·5
D.T.D. 41	Mild Steel Tube .	32 24*	28 17*	26·5 14*	22	45 35*	28 27*
D.T.D. 167	45-Ton Steel Tube .	45	40	—	—	—	—
D.T.D. 175	Chrome-Molybdenum Tube . . .	45 35*	—	40 30*(0·2%p)	—	—	—
D.T.D. 234	75-Ton Nickel-Chrome Steel Tube .	75	—	68 (0·2%p)	—	—	—

* Strength after welding.

(6) NON-CORRODIB

Specification No.	Material	Strength Values (Tons/sq. in.)					Lb./sq.
		f_t	f_y	f_p	f_s	f_b	E/10⁶
D.T.D. 67A	Low Tensile N.C. Steel Tube	25	18	18	18	42	28·5
D.T.D. 102A	35-Ton N.C. Steel Tube	35	30	30	24	52	29
D.T.D. 199	50-Ton N.C. Steel Tube	50		45 (0·2%p)	30	75	30·5
D.T.D. 203A	50-Ton N.C. Steel Tube	50		45 (0·2%p)	30	75	
D.T.D. 207	35-Ton N.C. Steel Tube	35		15 (0·1%p) 18 (0·2%p)	24	52	27
D.T.D. 211	50-Ton N.C. Steel Tube	50		45 (0·2%p)	30	75	25·5

rks	C	Si	Mn	S	P	Ni	Cr	Others
	CHEMICAL COMPOSITION (PER CENT							
lded . .	≯ 0·4	≯ 0·35	≯ 1·75	≯ 0·05	≯ 0·05	—	—	—
.	0·25 to 0·35	≯ 0·35	0·45 to 0·70	≯ 0·05	≯ 0·05	3 to 5	0·5 to 1·5	V ≯ [illegible] Mo ≯ [illegible] W ≯ [illegible]
.	≯ 0·20	—	—	≯ 0·05	≯ 0·05	—	—	—
. . .	≯ 0·3	≯ 0·35	≯ 1·75	≯ 0·05	≯ 0·05	—	—	—
pecial sections tubes below T35	≯ 0·3	≯ 0·35	≯ 1·75	≯ 0·05	≯ 0·05	—	—	—
elded .	≯ 0·5	≯ 0·35	≯ 1·75	≯ 0·05	≯ 0·05	Up to 3·75	—	—
. . .	≯ 0·18	≯ 0·3	≯ 1·5	≯ 0·05	≯ 0·05	—	—	—
.T.D. 149 .	0·25 to 0·45	0·10 to 0·30	0·40 to 0·80	≯ 0·05	≯ 0·05	—	[illegible] to 1·20	Mo [illegible] to [illegible]
Non-circular . . .	≯ 0·3	≯ 0·3	≯ 0·8	≯ 0·05	≯ 0·05	—	0·8 to 1·2	Mo 0·15 to 0·3
—	0·25 to 0·35	≯ 0·35	0·45 to 0·7	≯ 0·05	≯ 0·05	3 to 5	0·5 to 1·5	—

BES

marks	C	Si	Mn	S	P	Ni	Cr	Others
	CHEMICAL COMPOSITION (PER CENT							
—	≯ 0·15	≯ 0·50	—	≮ 0·05	≮ 0·05	≯ 1·0	≮ 12	—
o T1 . .	≯ 0·15	≯ 0·5	≮ 1·0	≮ 0·05	≮ 0·05	≯ 1·0	≮ 12	—
—	≯ 0·25	≯ 0·5	≯ 1·0	≯ 0·05	≯ 0·05	≮ 1·0	16 to 20	—
—	0·10 to 0·20	≯ 0·5	≯ 1·0	≯ 0·05	≯ 0·05	≯ 1·0	≮ 12	—
o T26, T35, and . . .	≯ 0·2	≮ 0·5	≯ 1·0	≯ 0·05	≯ 0·05	6·0 to 20·0	≮ 12·0	—
o T45 and T50 . . .	≯ 0·2	≮ 0·5	≯ 1·0	≯ 0·05	≯ 0·05	≮ 6·0	≮ 12·0	—

LIGH YS

(1) ALUMINIUM ALLO FORGINGS,

Specification No.	Material	Strength Values (Tons/sq. in.)					Lb./sq. in	Remarks
		f_t	f_y	f_p	f_s	f_b	E/10⁶	
5 L1	Duralumin Bar .	25	—	15	16	32	10·5	gings, Extru ns and Bars fo g not exceedin
L37	Duralumin Rivets .	25	—	15	16	32	—	—
L38	Aluminium Rivets	7	—	—	—	—	—	—
L39	Duralumin Bar . .	22	—	12	16	32	10·5	machining ab up to 6″ .
L40	Aluminium Alloy Bar .	27	—	21	16	33	—	nium R.R. 56 gings, Extru ns and Bars f g not exceed
D.T.D. 280	Aluminium Alloy Bar .	28	—	18	18	35	—	machining up Extrusions up . .
D.T.D. 290	Aluminium Alloy Bar	27	—	17	16	33	—	machining ab Extrusions ab . .
D.T.D. 363	Aluminium Alloy Bar	33	—	27	—	—	—	nium R.R.77 d sections ed parts.

S

ORGINGS, ETC.

Remarks	Specific Gravity	Chemical Composition (per Cent)						
		Cu	Mn	Mg	Si	Fe	Ti	Al
gings, Extruded s and Bars for ma- not exceeding 3″	2·85	3·5 to 4·5	0·4 to 0·7	0·4 to 0·7	≯ 0·7	≯ 0·7	≯ 0·3	The rest
—	2·85	3·5 to 4·5	0·4 to 0·7	0·4 to 0·7	≯ 0·7	≯ 0·7	≯ 0·30	The rest
—	2·75	Fe + Si ≯ 1·7		—	≯ 1·0	≯ 1·0	≯ 0·2	≮ 98
nachining above up to 6″ . .	2·85	3·5 to 4·5	0·4 to 0·7	0·4 to 0·7	≯ 0·7	≯ 0·7	≯ 0·3	The rest
ium R.R. 56 . gings. Extruded ns and Bars for ma- g not exceeding 3″	2·80	1·5 to 2·5	Ni 0·5 to 1·5	0·6 to 1·2	≯ 1·0	0·8 to 1·5	≯ 0·2	The rest
nachining up to 4″ Extrusions up to 3″	2·85	3·5 to 4·5	0·3 to 1·5	0·8 to 1·8	≯ 0·5	≯ 0·4	—	The rest
nachining above 4″ Extrusions above 3″	2·85	3·5 to 4·5	0·3 to 1·5	0·8 to 1·8	≯ 0·5	≯ 0·4	—	The rest
nium R.R.77 . d sections for ed parts.	2·90	1·5 to 3·0	Ni ≮ 1·0	2·0 to 4·0	≮ 0·6	≯ 0·6	≮ 0·3	Zn 4·0 – 6·0 Al The rest

(2) ALUMINIUM ALLO

Specification No.	Material	Strength Values (Tons/sq. in.)					Lb./sq. in.
		f_t	f_y	f_p	f_s	f_b	E/10^6
4 L3	Duralumin Sheet	25	—	15	16	32	10·5
2 L4	Hard Aluminium Sheet	9	—	—	—	—	10·5
2 L16	Half Hard Aluminium Sheet	7	—	—	5	15	10·5
L38	"Alclad" Sheet	24	—	13·5	16	32	9·7
D.T.D. 2[illegible]	Aluminium Alloy Sheet	27	—	21	—	—	—
D.T.D. 179A	Aluminium Mag. Alloy Sheet	22	—	15	—	—	—
D.T.D. 175A	Aluminium Mag. Alloy Sheet	16	—	12	—	—	—
D.T.D. 24[illegible]	Aluminium Alloy Sheet	18	—	14	—	—	—
D.T.D. 270	Aluminium Alloy Sheet and Strip	25	—	17·5	18	35	—
D.T.D. 275	Aluminium Alloy Sheet and Strip	26	—	16	16	33	—

ET AND STRIP

Remarks	Chemical Composition per Cent							
	C	Si	Mn	S	P	Ni	Cr	[illegible]
rseding D.T.D. 23B	≯ 0·15	≯ 0·5	≯ 0·70	≯ 0·50	≯ 0·70	≯ [illegible]	≮ [illegible]	—
—	≯ 0·1	≯ 0·5	—	—	—	≯ [illegible]	≮ [illegible]	—
. . . .	0·12 to 0·20	≯ 0·5	—	—	—	≯ 1·0	≮ 12	—
—	≯ 0·2	≯ 0·6	≯ 1·0	≯ 0·05	≮ 0·05	[illegible]	[illegible]	—
Low Stressed Parts, xhaust Manifolds, etc.	≯ 0·12	≯ 0·20	≯ 0·50	≯ 0·05	≯ 0·05	≯ 0·30	—	—
—	≯ 0·2	≯ 0·6	≯ 1·0	≯ 0·05	≯ 0·05	[illegible]	[illegible]	—
erseding D.T.D. 57B .	≯ 0·20	≮ 0·5	≯ 1·0	≯ 0·05	≯ 0·05	≮ [illegible]	≮ [illegible]	—
—	≯ 0·25	≯ 0·50	≯ 1·0	≯ 0·05	≯ 0·05	≯ 1·0	[illegible]	—
perseding D.T.D. 144 .	≯ 0·20	≮ 0·50	≯ 1·0	≯ 0·05	≯ 0·05	≮ 6·0	≮ 12	—
—	0·12 to 0·20	≯ 0·50	≯ 0·70	≯ 0·05	≯ 0·05	≯ 1·0	≮ 12	—
—	≯ 0·20	≯ 0·60	≯ 1·0	≯ 0·05	≯ 0·05	≯ 3·0	16 to 20	—

(3) ALUMINIUM Y CASTING

Specification No.	Material	Strength Values (Tons/sq. in.) f_t	f_y	f_p	f_s	f_b	Lb./sq. in. E/10⁶	Remarks
2 L5	Casting Alloy . .	9	—	—	5·5	13	—	ast .
L33	Aluminium Silicon Alloy Castings	10·5	—	—	—	15	9·5	—
L35	"Y" Alloy Castings .	14	—	—	—	21	—	s. .
D.T.D. 131A	Aluminium Alloy Castings . . .	16* 20†	—	15·5* 20†	—	24* 30†	—	inium R.R. t Treated
D.T.D. 133B	Aluminium Alloy Castings . .	11* 12·5†	—	7·5* 8†	—	16* 18†	—	inium R.R. t Treated
D.T.D. 240	Silicon Aluminium Alloy Castings	11	—	6	—	—	—	r Beta" .
D.T.D. 245	Silicon Aluminium Alloy Castings	15·5	—	13	—	—	—	r Gamma"
D.T.D. 250	Aluminium Alloy Castings . .	14* 20†	—	11·5* 13†	—	21* 30†	—	min D. He ated . . 211
D.T.D. 255	Aluminium Alloy Castings . .	18* 23·5†	—	17·5* 20†	—	27* 34†	—	min C. He ated .
D.T.D. 260	Aluminium Alloy Castings . .	18	—	13	—	—	—	22 .
D.T.D. 304	Aluminium Alloy Castings . .	18	—	14	—	—	—	226 . l not be h nodized .
D.T.D. 309	Aluminium Alloy Castings . .	19* 23†	—	18* 19·5†	—	27* 34†	—	minium R. at treated

* Sand cast † Chill cast

(4) ALUMINIUM OY TUB

Specification No.	Material	Strength Values (Tons/sq. in.) f_t	f_y	f_p	f_s	f_b	Lb./sq. in. E/10⁶	Rema
4 T4	Duralumin Tubes .	26* 25	—	18* 15	16	32	10·5	—
4 T9	Aluminium Tubes .	9†	—	—	5	15	10·5	—
D.T.D. 220A	Wrought Light Aluminium Alloy Tubes	26	—	22 ·2%	—	—	10·5	minium B

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* As supplied. Lower figures to apply if heat-treated during working.
† Up to 2" dia. Lower figures for larger sizes.

CASTINGS

Remarks	Specific Gravity	Chemical Composition (per Cent)						
		Cu	Mn	Mg	Si	Fe	Zn	Al
t	2·99	2·5 to 3·0	Ti ≯ 0·2[illegible]	[illegible] ≯ [illegible]	≯ [illegible]	≯ 0·[illegible]	[illegible] to [illegible]	The rest
—	2·70	—	≮ 0·5	Ti ≯ 0·2[illegible]	[illegible] to 13	≯ [illegible]6[illegible]	≯ [illegible]	The rest
. . . .	2·85	3·5 to 4·5	Ti ≯ 0·2	1·[illegible] to 1·7	≯ [illegible]	≯ [illegible]	Ni 1·8 to [illegible]	The rest
lum R.R. 53. reated . .	2·75	1·5 to 2·5	Ni 0·5 to 2·0	1·4 to 1·8	≯ [illegible]	1·[illegible] to 1·5	Ti [illegible] to [illegible]	The rest
lum R.R.50 reated . .	2·73	0·8 to 2·0	Ni 0·8 to 1·75	0·05 to 0·[illegible]	1·5 to 2·[illegible]	[illegible] to 1·4	Ti [illegible] to [illegible]	The rest
Beta" . . .	The rest	> 0·6	—	Fe > 0·6	10·[illegible] to 13·[illegible]	[illegible]	—	[illegible]
Gamma" . .	The rest	> 0·6	—	Fe > 0·6	10·[illegible] to 13·[illegible]	[illegible]	—	[illegible]
in D. Heat d . . . :11	2·79	2 to 3	Ni 1 to 2	0·5 to 1·0	1 to 1·4	1 to 1·4	Ce [illegible] to [illegible]	The rest
in C. Heat d . . .	2·79	2 to 3	Ni 1 to 2	0·5 to 1·0	1 to 1·4	1 to 1·4	Ce [illegible] to [illegible]	The rest
: . . .		4·0 to 4·6	> 0·3	0·1 to 0·3	[illegible]	[illegible]	[illegible]	[illegible]
; . . . not be heat treated dized . . .		4·0 to 4·6	Ni + Mg + Mn + Zn > 0·2		[illegible]	[illegible]	[illegible]	[illegible]
lum R.R.53C. treated . .	2·76	2 to 3	Ni 1 to 2	0·6 to 1·0	0·7 to 1·5	1·2 to 1·5	Ti ≮ 0·3	The rest

TUBES

Remarks	Specific Gravity	Chemical Composition (per Cent)						
		Cu	Mn	Mg	Si	Fe	Zn	Al
—	2·85	3·5 to 4·5	0·4 to 0·7	0·4 to 0·7	> 0·07	≯ 0·7	Ti 0·3	The rest
—	2·70	Fe + Si ≯ 1·7		—	≯ 1·0	≯ 1·0	—	98
lium R.R.56 .	2·75	1·5 to 2·5	Ni 0·5 to 1·5	0·4 to 1·0	≯ 1·0	0·8 to 1·5	Ti ≯ 0·12	The rest

pecification No.	Material	Strength Values (Tons/sq. in.)					Lb./sq. in.	Remarks
		f_t	f_y	f_p	f_s	f_b	$E/10^6$	
D.T.D. 88B	Magnesium Alloy Forgings, Stampings, Pressings	15	—	8	—	—	6	—
D.T.D. 142	Magnesium Alloy Bars	15	—	8	—	—	6	welding .
D.T.D. [illegible]	[illegible] Aluminium [illegible]	25	—	15	—	—	—	·63 . . .
D.T.D. 259	Magnesium Alloy Bars	17* 14†	—	11* 9†	—	—	—	—
D.T.D. [illegible]	Magnesium Alloy Bars, Extruded Sections and Forgings (Softened)	[illegible]	—	[illegible]	—	—	—	—

* Up to 2". † Above 2"

(6) MAGNESIUM ALLOY AND STRIP

pecification No.	Material	Strength Values (Tons/sq. in.)					Lb./sq. in.	Remarks
		f_t	f_y	f_p	f_s	f_b	$E/10^6$	
D.T.D. 118	Magnesium Alloy Sheets	11	—	—	—	—	6	r welding .
D.T.D. 177A	[illegible]	25	—	15	—	—	—	·63 . .

(7) MAGNESIUM CASTINGS

pecification No.	Material	Strength Values (Tons/sq. in.)					Lb./sq. in.	Remarks
		f_t	f_y	f_p	f_s	f_b	$E/10^6$	
D.T.D. 140A	Magnesium Alloy Castings	6	—	—	—	—	5·3	—
D.T.D. 136A	Magnesium Alloy Castings	8* 11†	—	4·5* 5·5†	—	—	—	1·83 . .

NICKEL ER ALLOY

pecification No.	Materia	Strength Values (Tons/sq. in.)					Lb./sq. in.	Remarks
		f_t	f_y	f_p	f_s	f_b	$E/10^6$	
D.T.D. 204	High Nickel Copper Alloy Rods, Wire and Rivets	28	—	—	—	—	25	" . . .
D.T.D. 328	Nickel-Chromium-Iron Sheets and Strips	35	—	—	—	—	31	el" . .

*Sand cast. †Chill cast.

FORGINGS, ETC.

Remarks	Al	Mn	Zn	Cu	Si	Mg	Total Impurities
	CHEMICAL COMPOSITION (PER CENT)						
—	≯ 11·0	≯ 1·0	≯ 1·5	—	—	The rest	≯ 1·5
for welding	≯ 0·2	≯ 2·5	≯ 0·2	≯ 0·2	≯ 0·4	The rest	≯ 0·5
2·63	The rest	0·3 to 0·6	Fe ≯ 0·75	—	—	6·5 to 7·25	—
—	≯ 11·0	≯ 1·0	≯ 1·5	—	—	The rest	≯ 1·5
—	—	—	—	—	—	—	—

ET AND STRIP

Remarks	Al	Mn	Zn	Cu	Si	Mg	Total Impurities
	CHEMICAL COMPOSITION (PER CENT)						
able for welding	≯ 0·2	≯ 2·5	≯ 0·2	≯ 0·2	≯ 0·4	The rest	≯ 0·5
Gr. 2·63	The rest	≯ 0·6	—	Fe ≯ 0·75	≯ 0·5	6·5 to 10·0	—

LOY CASTINGS

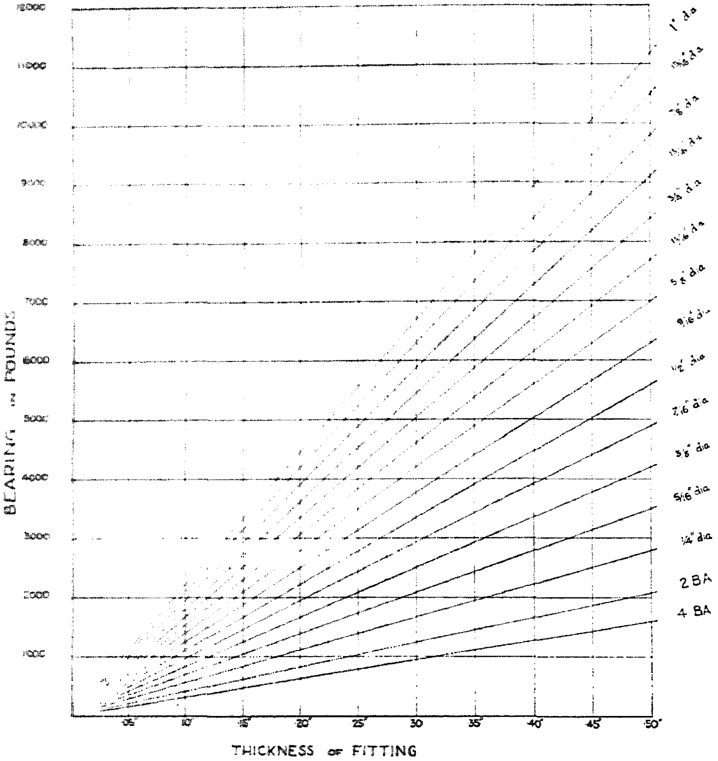
Remarks	Al	Mn	Zn	Cu	Si	Mg	Total Impurities
	CHEMICAL COMPOSITION (PER CENT)						
—	≯ 0·2	≯ 2·5	≯ 0·2	≯ 0·2	≯ 0·4	The rest	≯ 0·5
Gr. 1·83	9 to 11	≯ 0·5	≯ 3·5	—	—	The rest	≯ 1·5

OPPER ALLOY

Remarks	Al	Mn	Zn	Cu	Si	Mg	Total Impurities
	CHEMICAL COMPOSITION (PER CENT)						
"Monel"	Ni 64·0 to 70·0	0·3 to 2·0	Cu The rest	Fe ≯ 2·5	—		0·3
	Ni 75 to 85		Cr 12·0 to 15·0	≯ 10·0	—		

Bolt Strengths

The following curves serve as a basis for calculating the strengths of bolts in shear, tension, bending and bearing. They are all worked out on a figure of 10 tons/sq. in. They are thus applicable to any of the materials, in the foregoing tables, by the introduction of a factor obtained by proportioning the appropriate strength figure to 10. For example, the shear strength of a mild steel bolt (Specification S1) is obtained by multiplying the figure read off the curve by $\frac{23}{10}$, or 2·3. Similarly, the multiplying factor for a duralumin bolt in shear is $\frac{16}{10}$, or 1·6.

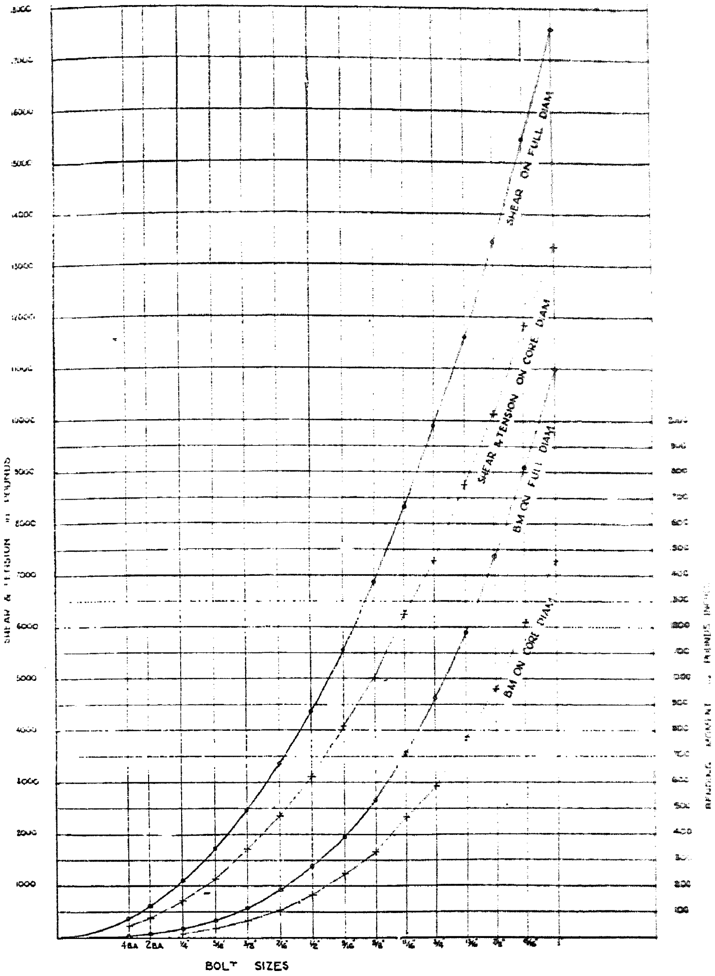


BEARING STRENGTHS OF BOLTS AT 10 TONS/SQ IN

For bending it is usual to take a maximum permissible stress midway between the ultimate tensile stress (f_t) and either the yield point (f_y) or the proof stress (f_p), whichever of these is known.

The "core diameter" curves are given with diffidence owing to the weakening effect of the thread cutting. Unless it is impossible to avoid it, the threaded portion of a bolt should never be under any stress other than tension.

The "Bearing Strength" curves are, of course, worked out on the full diameter of the bolt shank, since the threaded portion is quite unsuitable for taking bearing loads. The basic figure of 10 tons/sq. in.



SHEAR TENSILE & BENDING STRENGTHS OF BOLTS AT 10 TONS/SQ IN

makes the curves of universal application. Some designers may disagree with the strength of materials quoted in the Tables, but they may use the curves for whatever figure they choose by applying the appropriate factor.

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